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Emissions and power demand in optimal energy retrofit scenarios of the Finnish building stock by 2050

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ABSTRACT

Finland and the European Union aim to reduce CO_2 emissions by 80–100 % before 2050. This requires drastic changes in all emissions-generating sectors. In the building sector, all new buildings are required to be nearly zero energy buildings. However, 79 % of buildings in Finland were built before 2000, meaning that they lack heat recovery and suffer from badly insulated facades.

This study presents four large-scale building energy retrofit scenarios, showing the emission reduction potential in the whole Finnish building stock. Six basic building types with several age categories and heating systems were used to model the energy demand in the building stock. Retrofitted building configurations were chosen using simulation-based multi-objective optimisation and combined according to a novel building stock model.

After large-scale building retrofits, the national district heating demand was reduced by 25–63 % compared to the business as usual development scenario. Despite a large increase in the number of heat pumps in the system, retrofits in buildings with direct electric heating can prevent the rise of national electricity consumption. CO_2 emissions in the different scenarios were reduced by 50–75 % by 2050 using current emissions factors.

1. Introduction

Buildings account for 40 % of energy consumption in the European Union (EU). The Energy Performance of Buildings Directive (EPBD) was implemented to increase the energy efficiency of new buildings and start a shift towards nearly Zero Energy Buildings (nZEB). However, most buildings were built long before the implementation of the directive. For this reason, the EPBD was updated to include a call for large-scale renovation of the existing building stock. In Finland, 79 % of the building stock was built before 2000 (Statistics Finland, 2016), which shows the importance of the updated directive.

In 2011, the EU decided on climate goals where the aim was to reduce greenhouse gas emissions by 80 % from 1990 levels by 2050 (European Commission, 2012). These goals were updated in 2020 to aim for complete emission neutrality (European Commission, 2016). Reaching EU emission targets requires extensive planning and actions in both the building sector and in the energy infrastructure. For example, the methods (Henning & Palzer, 2014) and results (Palzer & Henning, 2014) for a German plan for national decarbonisation have been presented. While the energy system was modelled in detail, the changes in the building stock were reduced to a single efficiency curve. A more detailed examination of the building stock would provide valuable information on the specific means that should be used in buildings. The problem of the building sector's energy consumption has been identified

Abbreviations: AAHP, air-to-air heat pump; AWHP, air-to-water heat pump; CAV, constant air volume (ventilation); CO_2, carbon dioxide; DH, district heating; EAHP, exhaust air heat pump; EPBD, energy performance of buildings directive; ETS, emission trading system; GSHP, ground-source heat pump; HP, heat pump; HR, heat recovery; PV, solar photovoltaic panel; ST, solar thermal collector; VAV, variable air volume (ventilation).

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around the world. For example, in China, over 2000 billion m^2 of floor space is in need of an energy retrofit (Huo et al., 2019).

Several studies on the building stock can be found in the literature. The energy-saving potential in the Finnish building stock was examined in Tuominen, Forsström, & Honkatukia (2013). With a high deployment of new low energy and passive houses and highly prevalent energy retrofits, heating demand was estimated to decrease by over 50 %. However, the retrofit effects were modelled as simple percentage drops in building energy consumption without specifying exact retrofit measures. The efficacy of building retrofits in a cooling-dominated climate was shown when the Saudi Arabian residential building stock was modelled (Krarti, Aldubyan, & Williams, 2020). A 61 % reduction in national CO_2 emissions was found possible. The study included hourly simulations of a total of 54 residential building configurations, with different types, ages and locations. The Brazilian office building stock was modelled using reference buildings, dynamic simulation and cost-optimal pathway analysis Alves, Machado, de Souza, and de Wilde (2018). One to four different energy-saving measures were utilised separately and together to find the most cost-effective retrofit concepts. There are also climate differences within countries, as pointed out in (Ma, Liu, & Shang, 2021). Green retrofitting should take into account regional climate differences to provide optimal solutions appropriate for the local conditions. Correction coefficients were suggested to improve the applicability of standard retrofit solutions to different climates. The use of building archetypes can be problematic when individual systems are generalised to represent the whole building stock. A study of Japanese office buildings found that not accounting for details such as differences in HVAC systems could cause an error of 15 % when estimating building stock energy consumption (Kim et al., 2019).

Differences in system details can be accounted for in multi-objective optimisation studies of individual buildings. Optimising the cost and environmental impact of building energy retrofits at the same time provides a Pareto optimal set of deep retrofit solutions. A Pareto optimal solution is one where the value of one objective cannot be improved without making another objective worse. Thus, the final retrofit configuration can be chosen from a variety of potential solutions, some both expensive and impactful and some affordable, but having low impact. Optimised configurations for different building types can then be combined to provide a view of the whole building stock. A study on building performance optimisation presented a review of decision-making models, measures, software, etc. used for designing retrofits of existing buildings (Hashempour, Taherkhani, & Mahdikhani, 2020). Genetic algorithms were clearly the most common optimisation method. Building simulation tools were more distributed, though Design Builder was the most common one, with a 16 % share. About half of the reviewed studies were related to residential buildings, but commercial and educational buildings were also a common subject. For example, simulation-based optimisation of building retrofits in cold climates has been performed on apartment buildings in Finland (Niemelä, Kosonen, & Jokisalo, 2017) and Sweden (Shadram, Bhattacharjee, Lidelöw, Mukkavaara, & Olofsson, 2020), on office buildings in Norway (Rabani, Bayera Madessa, Mohseni, & Nord, 2020) and Finland (Niemelä, Levy, Kosonen, & Jokisalo, 2017), and on educational buildings in Finland (Niemelä, Kosonen, & Jokisalo, 2016). The Pareto optimal solutions identified can be used to choose a retrofit method that meets certain criteria, such as some energy efficiency standard or budget limit.

A Swiss building stock model utilised an agent-based method, which helps forecast the development of the building stock under different policies and energy prices (Nägeli, Jakob, Catenazzi, & Ostermeyer, 2020). Bottom-up aggregation of the building stock has also been presented for Germany (Kotzur et al., 2020) with 200 residential building types. The model was used to estimate building stock energy consumption in 2050. Peak electric power consumption (the maximum hourly power over the year) was doubled in rural areas due to the increased use of heat pumps. This issue has also been raised in the Swedish context, as the major uptake of heat pumps is expected to increase peak power consumption and thus increase the emissions of electricity consumption through the use of fossil-based peak power plants (Dodoo, 2019). However, heat pumps can also reduce the use of direct electric heating and thus compensate for the increases in power demand in other buildings (Hirvonen, Jokisalo, & Kosonen, 2020).

No archetypes or dynamic simulations were used to model the building stock of a region in Northern Italy (D'Alonzo et al., 2020). Instead, available data on the building location, shape, size and energy certificates was used to estimate building-level energy consumption at the regional scale. The energy saving potential of the Danish building stock was estimated using a hybrid model, which combined both detailed building physics-based models and statistical modelling (Brøgger, Bacher, & Wittchen, 2019). The model improved the accuracy of building stock energy calculation, but predicted too many average demand cases and too few extreme demand cases. Since buildings exist as part of a wider energy system, the connection between large-scale power generation and buildings needs to be established. This kind of balancing between building-side retrofits and district heating investments has been explored in the Swedish context in (Romanchenko, Nyholm, Odenberger, & Johnsson, 2020). The least-cost option included the installation of building-side thermal insulation and heat recovery (HR) as well as investments in centralised heat generation and large-scale thermal energy storage.

Residential buildings are the most common building type, which is why many studies focus on them. A Swedish study used four building types for modelling the detached house building stock (Ekström & Blomsterberg, 2016). It was estimated that energy consumption in detached houses could be lowered by 65–75 %, even if most buildings could not be renovated to passive house standards. In a Finnish context, detached houses were modelled using four age classes and five main heating systems (Hirvonen, Jokisalo, Heljo, & Kosonen, 2019). After deep energy retrofits, CO_2 emissions could be reduced by 79–92 % when switching to heat pumps and by 20–75 % otherwise. A Danish study found that 50 % savings in primary energy consumption were possible in apartment buildings (Rose, Thomsen, Mørck, Gutierrez, & Jensen, 2019), in line with the Danish government's goals. Further reductions were deemed feasible with some extra financial investment. As major energy retrofits are not possible in every building, it was suggested that deep retrofits would be performed on the remaining buildings, as opposed to only doing the most cost-effective actions. Energy demand in buildings may also be affected by external factors. Dense urban environments generate a heat island effect, which may increase cooling demand in hot climates (Yang et al., 2021). Cooling demand can be reduced by adding vegetation into the urban environment.

Detailed studies of the Finnish building sector are still lacking. How do the building retrofits influence Finnish district heating and electricity demand? What is the influence of heating systems and investment levels? How do the retrofits affect existing power plants and the future of combined heat and power generation (CHP)? Answering these questions requires hourly demand data so that the variable nature of modern renewable energy is accounted for. Retrofit actions in the buildings should also be compared to investments in the energy grid and power plants.

The large-scale deep retrofit of existing buildings has strong potential for reducing national carbon dioxide emissions in Finland. However, the optimisation of building retrofits is typically done at the level of individual buildings. To reach the long-term national and international emissions reduction obligations, large-scale work on the level of the whole building stock is needed. The speed at which large-scale retrofits can be done needs to be taken into account. This study looks into the Finnish building stock and examines various scenarios for large-scale retrofits. The main contribution of the article is to show retrofit pathways with different priorities given for district heating and electrification. How and how fast can we reach various end goals and what are the cumulative CO_2 emissions produced while getting there? Five retrofit scenarios are examined to see how the hourly demand for heating and electricity are changed in the whole building stock. The results are useful for policymakers and energy market actors who wish to evaluate how large-scale retrofits in the building stock could influence national energy use. The study also serves as a stepping stone for an improved model that combines the energy system and building stock models to provide a comprehensive view of the issue.

2. Methods and materials

2.1. Overview of the simulation arrangement

The study aimed to calculate the hourly district heating and electricity consumption of buildings after deep energy retrofits in the Finnish building stock. This data could then be used for preliminary emission calculations and more detailed energy system analysis. To reach this goal, energy profiles of individual buildings were combined according to their shares of the building stock and then developed according to specific long-term scenarios. Fig. 1 shows the components used to form the scenarios. First, the type of buildings representing the building stock were modelled and then these buildings were optimised to find cost-effective retrofit measures. Hourly profiles of the individual buildings were combined in the building stock model, which represents the current situation of the number of buildings and heating systems and provides a forecast of changes up to 2050. Finally, the different scenarios show the emission reducing impact of different retrofit levels and large-scale heating system choices.

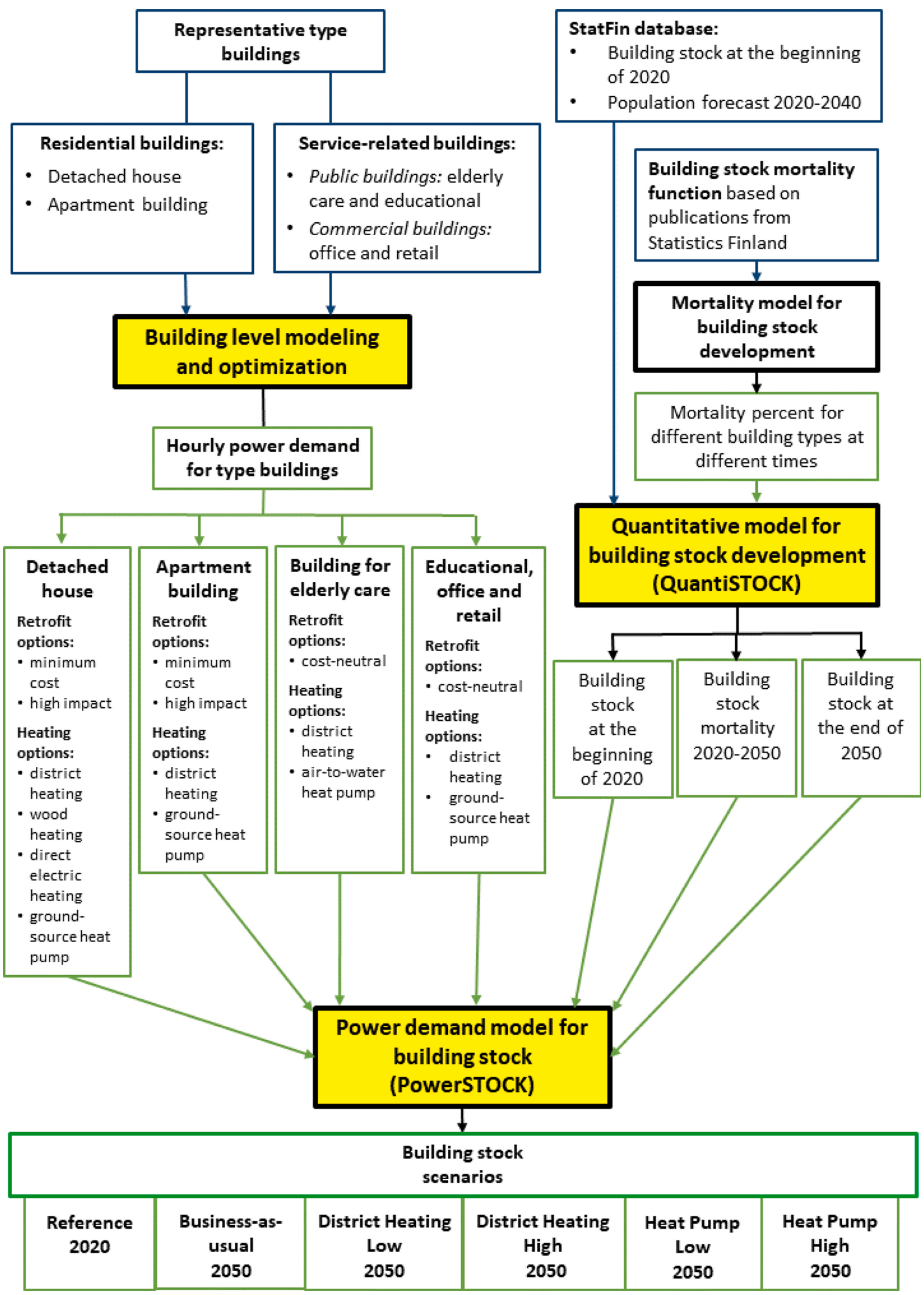

Fig. 1. Modelling procedures and relationships between different models.

2.2. Building types representing the building stock

The Finnish building stock is composed of buildings of various ages and many different uses, although it is dominated by residential buildings. Energy retrofits in different building types have been studied in previous research papers. In this paper, the results on optimal building retrofits from previous studies are combined to get a national view of the long-term development of energy use and emissions in buildings. To model the whole of the building stock, six types of buildings have been chosen: detached houses (Hirvonen et al., 2019b), multi-storey apartment buildings (Hirvonen, Jokisalo, Heljo, & Kosonen, 2018), elderly care buildings (Jokisalo, Sankelo, Juha, Sirén, & Kosonen, 2019), office buildings (Niemelä, Levy et al., 2017), educational buildings (Niemelä et al., 2016) and retail buildings (Saari & Airaksinen, 2012). The chosen building types cover 79 % of the Finnish building stock and 95 % of residential and service buildings, thus adequately representing the whole building stock (Statistics Finland, 2017). As shown in Fig. 2, the vast majority of the building stock are residential buildings. Residential buildings have long lifetimes and buildings from different periods with different features exists at the same time. Thus, apartment buildings and single-family houses were divided into four age categories to show the retrofit potential in more detail. Service buildings are typically rebuilt or retrofitted more often and thus they were modelled using only a single age category. Industrial and warehouse buildings were not examined, because they are included in the manufacturing statistics, not the building sector. The 'Other' category contained a very heterogenous mix of buildings and no separate model was produced. Instead, those buildings were modelled as the 'Retail' building type. The building types and their retrofit options are presented in the next section.

2.2.1. Simulation and optimisation of buildings

The retrofit optimisation of each building type was handled the same way:

1) The building was simulated with the dynamic building energy simulation software, IDA-ICE (EQUA Simulation, 2019).
2) The retrofit measures of the created reference building model were optimised using the multi-objective optimisation tool MOBO (Palonen, Hamdy, & Hasan, 2013).

The calculation of each building type started with the creation of the reference building model in IDA-ICE, which has been shown to produce accurate results of building energy consumption EQUA Simulation (2010). The properties of this building matched the Finnish building code of the assumed construction period. The simulation model was then connected to MOBO, which utilises the genetic algorithm NSGA-II to solve a multi-objective optimisation problem (Deb, Pratap, Agarwal, & Meayarivan, 2002). No new optimisation runs were performed for this compilation study. Instead, the input data for the building stock calculations was based on the retrofit configurations obtained in previous optimisation studies, which had slightly differing optimisation objectives. The minimised objectives were the life cycle cost and either CO_2 emissions (for residential buildings) or primary energy consumption (for other building types). The selection of objectives was in the earlier studies for each building type and could not be changed anymore. However, similar results were obtained using both objectives, due to the strong correlation between CO_2 emissions and primary energy consumption. Thus, this should not have significant influence on the results on the building stock level. The optimisation process is described in Fig. 3. First, the optimisation tool generated an initial set of possible retrofit configurations. Then, each configuration was simulated using IDA-ICE. The generated results were evaluated in MOBO and new potential retrofit configurations were generated by mixing features of the best solutions in the latest iteration (crossover), with some randomisation added (mutation). This cycle was repeated until the expected number of generations was calculated. Using the method, several Pareto optimal solutions were generated for each building type. In a Pareto optimal solution, one objective cannot be improved without making another worse. Out of these sets of optimal solutions, a few cases were selected for use in the building stock calculations. The emission cutting methods included retrofits of the building envelope, installing new energy generation and heat recovery systems and retrofitting the ventilation system. There were some differences in the specific options included in the retrofitting of different building types. The optimisation objectives and retrofit options used for each building type are shown in Table 1. However, not every retrofit measure was always implemented even if available, because the actual retrofit configuration was determined by the optimisation algorithm.

2.2.2. Apartment buildings

Apartment buildings represent 21 % of the Finnish building stock. Thus, a detailed optimisation study on deep energy retrofits in four different categories of Finnish apartment buildings was done in (Hirvonen, Jokisalo et al., 2018), looking into life cycle cost (LCC) and CO_2 emissions. How the optimal retrofits affected heating and electric power consumption was reported in (Hirvonen, Jokisalo, Heljo, & Kosonen,

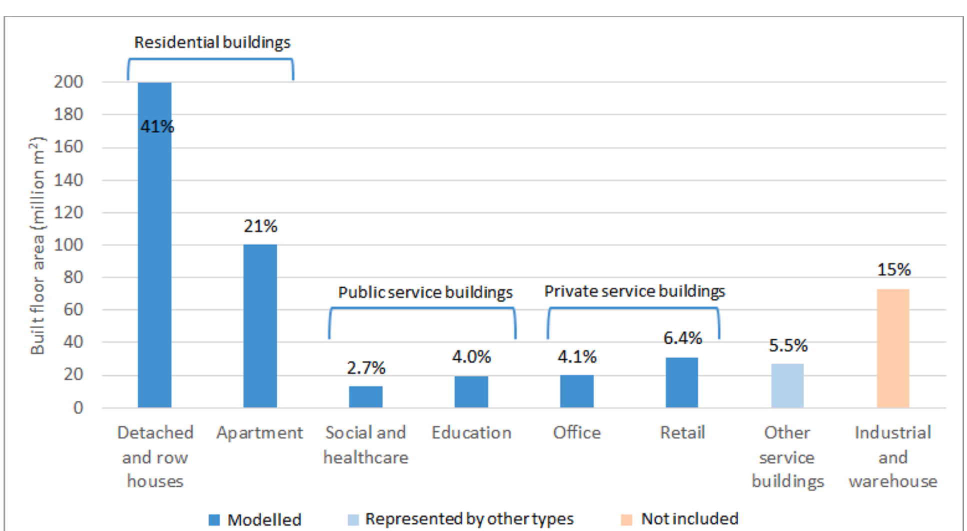

Fig. 2. The amount of built area of various Finnish building types.

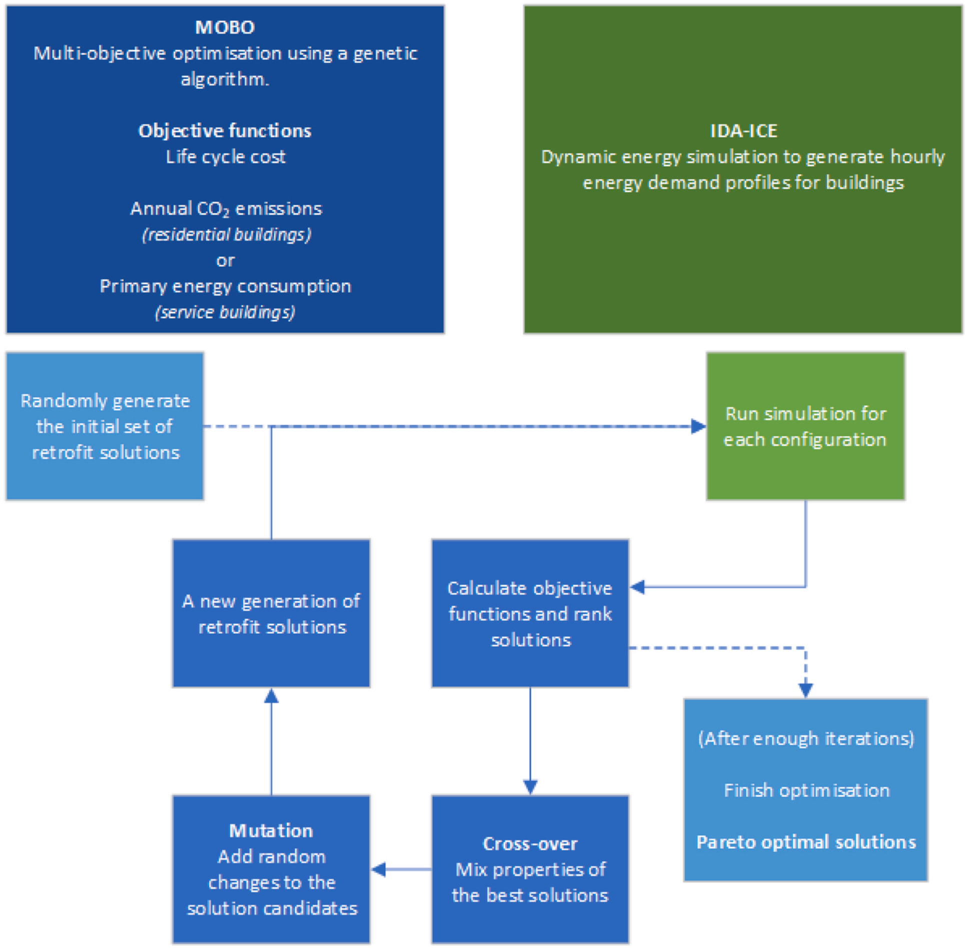

Fig. 3. Optimisation of energy retrofits in buildings.

Table 1
Optimisation objectives and retrofit options used in different building types.

	Retrofit options used in different building types					
Optimisation objectives	**Apartment**	**Single-family**	**Elderly**	**Educational**	**Office**	**Retail**
Minimize LCC and CO_2	x	x				
Minimize LCC and primary energy			x	x	x	x
Retrofit measures	**Apartment**	**Single-family**	**Elderly**	**Educational**	**Office**	**Retail**
Thermal insulation of walls	x	x	x	x	x	
Thermal insulation of roof	x	x	x	x	x	
New doors	x	x				
New windows	x	x	x	x	x	
Blinds between window panes					x	
Mechanical ventilation with HR	x	x	x	x	x	
VAV ventilation	x	x			x	
Sewage heat recovery	x					
Convert oil boiler to wood boiler		x				
GSHP	x	x		x	x	x
EAHP	x					
AWHP			x			
AAHP		x				
Low temperature radiators	x	x				
Solar thermal	x	x	x			
Solar electric (PV)	x	x	x	x		x
Energy efficient lighting					x	
Automated lighting control			x		x	

2019). The reference buildings in the study all used district heating, but the impacts of changing the heating system to exhaust air or ground-source heat pumps were also considered. Other considered retrofitting measures were improved thermal insulation of external walls and roof, the installation of energy-efficient doors and windows, solar electric panels (PV) and solar thermal collectors (ST) and heat recovery from ventilation and sewage systems.

The original multi-objective optimisation study produced several Pareto optimal solution sets, out of which four levels of optimal building retrofits with higher or lower emission impacts were identified for each age category. Out of these solutions, two cases were selected for building stock scenario studies: the cost-neutral solutions (case C), and the higher impact deep retrofit scenarios (case B). The cost-neutral solutions had a life cycle cost equal to the unrenovated reference case. The high impact solutions were chosen from the midpoint of the cost-neutral and the most expensive solutions. The details related to energy systems and efficiency are shown in Table 2.

2.2.3. Detached houses

Detached and terraced houses form the largest part of the Finnish building stock. Optimal deep energy retrofits in four age categories of detached houses were found in (Hirvonen et al., 2019b). Potential impacts on hourly power were analysed in (Hirvonen et al., 2020). For the detached houses, several main heating systems were utilised: oil and wood boiler heating, direct electric heating, ground-source heat pump and district heating. However, no oil heating remained in 2050 in any of the retrofit scenarios. The energy retrofits considered in the detached houses included improved thermal insulation, low U-value windows, installation of solar energy, ventilation retrofits and the installation of air-to-air heat pumps. Out of the numerous Pareto optimal solutions, four solutions in each case were identified. Two of these were utilised in this study: the lowest cost solution (case D) and the average cost high impact solution (case B). The details of the detached house properties are shown in Tables 2–5.

Heating demand for the detached houses were altered from the original source (Hirvonen et al., 2019b) by taking into account the low efficiency of oil and pellet boilers. The efficiency was 0.81 for the oil boiler and 0.75 for the pellet boiler (Lehtinen, 2017). This increased the fuel demand and emissions of the chosen cases compared to the original source (Table 6).

2.2.4. Elderly care buildings

An optimisation study of deep energy retrofits in elderly care buildings was done in (Jokisalo et al., 2019). This type of building represents a part of the municipal or public service buildings, the social and healthcare building category. Two main heating systems were considered: district heating and air-to-water heat pump (A2WHP). Cost-neutral levels of retrofitting (LCC the same as in reference case) were used for this building stock study.

The retrofit measures were the installation of mechanical supply and exhaust ventilation with heat recovery, improved thermal insulation of external walls and roof, installation of energy-efficient windows, automated lighting control, and the use of both solar thermal and solar electric systems. Details of building properties before and after energy renovation can be seen in Table 7.

2.2.5. Educational buildings

Educational buildings or schools represent the rest of the public service building sector. The building used here is a large university campus building, studied in (Niemelä et al., 2016). The main heating system options were district heating and ground-source heat pumps. Cost-neutral retrofit scenarios were chosen from the optimisation results to be used in the building stock calculations.

The used measures in the retrofitted buildings were replacing windows, installing ventilation heat recovery and installing solar electric panels and solar thermal collectors. With GSHP there were no solar thermal collectors. Details of building properties before and after energy renovation can be seen in Table 7.

2.2.6. Office buildings

Office buildings are part of the private service buildings group. They often have high internal heat gains, due to large window-to-wall ratios and heat emitting office equipment. Cost-optimality, indoor conditions and energy performance of office building retrofits were studied in (Niemelä, Levy et al., 2017). The multi-objective optimisation generated many Pareto-optimal solutions, out of which the cost-optimal cases using district heating and ground-source heat pumps were used in the formation of the building stock scenarios.

The utilised retrofit measures in the office buildings were low U-value windows, ventilation heat recovery, variable air volume ventilation, LED lighting and solar panels. The district heated case included additional thermal insulation of the roof, while the GSHP case included

Table 2
Properties of the apartment buildings.

Case	Building envelope U-values				Building service systems						
	Walls W/m^{2}K	Roof W/m^{2}K	Doors W/m^{2}K	Windows W/m^{2}K	Ventilation system (HR eff.)	Radiator temp °C/°C	HP capacity kW$_{th}$	Backup heating	Sewage HR	PV kW	ST m^2
AB1 Ref	0.81	0.47	2.2	1.7	Exhaust (0 %)						
AB1 DH C	0.81	0.08	2.2	0.7	Exhaust (0 %)	70/40			HP	30	55
AB1 DH B	0.36	0.08	2.2	0.8	Balanced (72 %) + VAV	70/40			HX	30	55
AB1 GSHP C	0.36	0.08	0.7	0.7	Exhaust (0 %)	45/35	110	Electric	HP	35	60
AB1 GSHP B	0.23	0.1	0.7	0.8	Balanced (72 %) + VAV	45/35	115	Electric	HX	35	0
AB2 Ref	0.34	0.26	1.4	1.7	Exhaust (0 %)						
AB2 DH C	0.34	0.26	0.7	1	Exhaust (0 %)	70/40			HX	25	100
AB2 DH B	0.36	0.1	0.7	0.7	Balanced (72 %) + VAV	70/40			HP	25	100
AB2 GSHP C	0.34	0.26	1.4	0.7	Exhaust (0 %)	65/40	35	Electric	HP	35	25
AB2 GSHP B	0.34	0.1	0.7	0.7	Balanced (72 %) + VAV	45/35	60	Electric	HX	35	90
AB3 Ref	0.25	0.17	1.4	1.4	Balanced (60 %)	70/40					
AB3 DH C	0.25	0.07	1.4	1.4	Balanced (60 %) + VAV	70/40			HX	15	50
AB3 DH B	0.25	0.06	0.7	1.4	Balanced (60 %) + VAV)	70/40			HP	15	95
AB3 GSHP C	0.25	0.06	0.7	1.4	Balanced (60 %) + VAV	70/40	25	Electric	HX	20	60
AB3 GSHP B	0.25	0.06	0.7	1.4	Balanced (60 %) + VAV	45/35	60	Electric	HX	20	65
AB4 Ref	0.17	0.09	1	1	Balanced (65 %)	45/35					
AB4 DH C	0.17	0.09	1	1	Balanced (65 %) + VAV	45/35			HX	15	45
AB4 DH B	0.17	0.06	0.7	1	Balanced (65 %) + VAV	45/35			HP	15	95
AB4 GSHP C	0.17	0.09	1	1	Balanced (65 %) + VAV	45/35	25	Electric	HX	25	30
AB4 GSHP B	0.17	0.06	0.7	0.6	Balanced (65 %) + VAV	45/35	35	Electric	HX	15	35

Balanced: Mechanical balanced ventilation with heat recovery.
Exhaust: Mechanical exhaust ventilation HP: Heat pump.
HR: Heat recovery.
HX: Heat exchanger PV: Solar photovoltaic panels.
ST: Solar thermal collectors.
VAV: Variable air volume (demand-based) ventilation.

Table 3
Properties of the detached single-family houses built before 1976, SH1.

Case	Building envelope U-values (W/m^2K)				Ventilation system	Radiator temp.	GSHP cap.	AAHP cap.	ST	PV
SH1	Walls	Roof	Doors	Windows	- (HR eff)	°C/°C	kW_{th}	kW_{th}	m^2	kW_p
DH Ref	0.58	0.34	1.4	1.8	Natural	70/40	0	0	0	0
DH D	0.2	0.1	1.4	1.8	Natural	70/40	0	2	2	0
DH B	0.1	0.1	1.4	0.6	Natural	70/40	0	3	18	7
Wood Ref	0.58	0.34	1.4	1.8	Natural	70/40	0	0	0	0
Wood D	0.2	0.1	1.4	1.8	Natural	70/40	0	2	2	0
Wood B	0.1	0.09	1.4	0.6	Natural	70/40	0	5	16	5
Elec Ref	0.58	0.34	1.4	1.8	Natural	–	0	0	0	0
Elec D	0.15	0.09	1.4	1.8	Balanced (75 %) + VAV	–	0	2	6	9
Elec B	0.1	0.09	1	0.6	Balanced (75 %)+ VAV	–	0	3	14	8
Oil Ref	0.58	0.34	1.4	1.8	Natural	70/40	0	0	0	0
GSHP D	0.2	0.12	1.4	1.8	Natural	70/40	7	0	0	10
GSHP B	0.1	0.1	1.4	0.6	Natural	40/30	8	0	8	9

Balanced: Mechanical balanced ventilation with heat recovery.
Natural: Natural stack ventilation PV: Solar photovoltaic panels.
ST: Solar thermal collectors.
VAV: Variable air volume (demand-based) ventilation.

Table 4
Properties of the detached single-family houses built between 1976 and 2002, SH2.

Case	Building envelope U-values (W/m^2K)				Ventilation system	Radiator temp.	GSHP	AAHP	ST	PV
SH2	Walls	Roof	Doors	Windows	- (HR eff)	°C/°C	kW_{th}	kW_{th}	m^2	kW_p
DH Ref	0.28	0.22	1.4	1.6	Exhaust	70/40	0	0	0	0
DH D	0.19	0.08	1.4	1.6	Exhaust	70/40	0	3	0	0
DH B	0.1	0.08	1	0.6	Exhaust	70/40	0	5	18	7
Wood Ref	0.28	0.22	1.4	1.6	Exhaust	70/40	0	0	0	0
Wood D	0.28	0.08	1.4	1.6	Exhaust	70/40	0	3	0	0
Wood B	0.12	0.08	1.4	0.6	Exhaust	70/40	0	5	20	5
Elec Ref	0.28	0.22	1.4	1.6	Exhaust	–	0	0	0	0
Elec D	0.19	0.08	1.4	1.6	Exhaust	–	0	5	6	7
Elec B	0.08	0.08	0.8	0.6	Exhaust	–	0	4	20	7
Oil Ref	0.28	0.22	1.4	1.6	Exhaust	70/40	0	0	0	0
GSHP D	0.28	0.08	1.4	1.6	Exhaust	70/40	7	0	0	10
GSHP B	0.08	0.08	1	0.8	Exhaust	40/30	6	0	12	7

Exhaust: Mechanical exhaust ventilation.
PV: Solar photovoltaic panels.
ST: Solar thermal collectors.

Table 5
Properties of the detached single-family houses built between 2003 and 2009.

Case	Building envelope U-values (W/m^2K)				Ventilation system	Radiator temp.	GSHP	AAHP	ST	PV
SH3	Walls	Roof	Doors	Windows	- (HR eff)	°C/°C	kW_{th}	kW_{th}	m^2	kW_p
DH Ref	0.25	0.16	1.4	1.4	Balanced (60 %)	40/30	0	0	0	0
DH D	0.25	0.08	1.4	1.4	Balanced (60 %) + VAV	40/30	0	1	2	0
DH B	0.1	0.09	1.4	0.8	Balanced (75 %) + VAV	40/30	0	5	14	7
Wood Ref	0.25	0.16	1.4	1.4	Balanced (60 %)	40/30	0	0	0	0
Wood D	0.25	0.08	1.4	1.4	Balanced (60 %) + VAV	40/30	0	1	2	0
Wood B	0.1	0.07	1	0.6	Balanced (75 %) + VAV	40/30	0	5	10	2
Elec Ref	0.25	0.16	1.4	1.4	Balanced (60 %)	–	0	0	0	0
Elec D	0.17	0.07	1.4	1.4	Balanced (60 %) + VAV	–	0	3	6	9
Elec B	0.1	0.07	1.4	0.6	Balanced (75 %) + VAV	–	0	4	14	8
Oil Ref	0.25	0.16	1.4	1.4	Balanced (60 %)	40/30	0	0	0	0
GSHP D	0.25	0.1	1.4	1.4	Balanced (60 %) + VAV	40/30	6	0	0	10
GSHP B	0.08	0.07	1.4	0.6	Balanced (75 %) + VAV	40/30	7	0	10	9

Balanced: Mechanical balanced ventilation with heat recovery.
PV: Solar photovoltaic panels.
ST: Solar thermal collectors.
VAV: Variable air volume (demand-based) ventilation.

automated lighting control and the use of window blinds. Details of building properties before and after energy renovation can be seen in Table 7.

2.2.7. Retail buildings

Retail buildings are another building type in the private service buildings groups. A previously defined building archetype was downgraded to a past building code to provide the old reference building Saari and Airaksinen (2012). The building in question is a retail building

Table 6
Properties of the detached single-family houses built after 2010, SH4.

Case	Building envelope U-values (W/m^2K)				Ventilation system	Radiator temp.	GSHP	AAHP	ST	PV
SH4	Walls	Roof	Doors	Windows	- (HR %)	°C/°C	kW_{th}	kW_{th}	m^2	kW_p
DH Ref	0.17	0.09	1	1	Balanced (65 %)	40/30	0	0	0	0
DH D	0.17	0.09	1	1	Balanced (65 %) + VAV	40/30	0	1	4	0
DH B	0.07	0.07	0.8	1	Balanced (75 %) + VAV	40/30	0	4	18	7
Wood Ref	0.17	0.09	1	1	Balanced (65 %)	40/30	0	0	0	0
Wood D	0.17	0.09	1	1	Balanced (65 %) + VAV	40/30	0	1	4	0
Wood B	0.07	0.06	0.8	1	Balanced (65 %) + VAV	40/30	0	5	20	7
Elec Ref	0.17	0.09	1	1	Balanced (65 %)	–	0	0	0	0
Elec D	0.17	0.07	1	1	Balanced (65 %) + VAV	–	0	3	6	9
Elec B	0.08	0.06	1	0.6	Balanced (75 %) + VAV	–	0	5	14	7
Oil Ref	0.17	0.09	1	1	Balanced (65 %)	40/30	0	0	0	0
GSHP D	0.17	0.09	1	1	Balanced (65 %)	40/30	5	0	0	10
GSHP B	0.08	0.07	1	1	Balanced (75 %) + VAV	40/30	14	0	20	7

Balanced: Mechanical balanced ventilation with heat recovery
PV: Solar photovoltaic panels
ST: Solar thermal collectors
VAV: Variable air volume (demand-based) ventilation

Table 7
Properties of the service buildings.

Case	Building envelope U-values			Building service systems						
	Walls	Roof	Windows	Ventilation system	Ventilation control	HP capacity	Backup heating	PV	ST	Other
Elderly care	W/m^2K	W/m^2K	W/m^2K	(HR eff)		kW_{th}		kW	m^2	
DH Ref	0.7	1.22	2.9	Exhaust (0 %)	CAV + sched	–	–	0	0	
DH neutral	0.27	0.08	0.6	Balanced (72 %)	CAV + sched	–	–	95	119	Automated lighting control
AWHP neutral	0.17	0.08	0.5	Balanced (72 %)	CAV + sched	175 (81 %)	Electric	153	118	Automated lighting control
Educational										
DH Ref	0.54	0.17	2.8	Balanced (0 %)	CAV + sched		–	0	0	
DH neutral	0.54	0.17	1	Balanced (77 %)	CAV + sched		–	347	168	
GSHP neutral	0.54	0.09	0.7	Balanced (77 %)	CAV + sched	42 (3.3 %)	DH	484	0	
Office										
DH Ref	0.35	0.29	2.1	Balanced (0 %)	CAV + sched	0	–	0		
DH neutral	0.35	0.1	0.6	Balanced (77 %)	VAV, CO_2+T	0	–	74		LED lights
GSHP neutral	0.35	0.29	0.7	Balanced (77 %)	VAV, CO_2+T	276 (104 %)	DH	76		Automated lighting control, LED lights
Retail										
DH Ref	0.28	0.22	1.4	Balanced (60 %)	CAV + sched		–	0	0	
DH neutral	0.28	0.22	1.4	Balanced (60 %)	CAV + sched		–	620	0	
GSHP neutral	0.28	0.22	1.4	Balanced (60 %)	CAV + sched	121 (67 %)	DH	650	0	

Balanced: Mechanical balanced ventilation with heat recovery.
CAV: Constant air volume ventilation.
Exhaust: Mechanical exhaust ventilation.
PV: Solar photovoltaic panels.
Sched: Schedule.
ST: Solar thermal collectors.
VAV: Variable air volume (demand-based) ventilation.

dominated by a large hall-like space, i.e. a hardware store. Optimisation of the building envelope was not done for this building type. Instead, only cost-neutral levels of solar panel installations were considered. District heating and ground-source heat pumps were used as the main heating systems. Details of building properties before and after energy renovation can be seen in Table 7.

2.2.8. Other building types

The six building types represent 79 % of all buildings in the Finnish building stock and 94.5 % of residential and service buildings, which was the main target of analysis. The remaining service buildings such as traffic and assembly buildings were considered too heterogeneous to model in detail. For simplicity, all the remaining service buildings (5.5 % of the building stock) were modelled as retail and office buildings. Industrial and warehouse buildings (15 %) were not included at all, as they are considered part of the manufacturing sector rather than the building sector.

2.3. Projection of building stock development

To estimate the impact of different energy saving pathways at the building stock level, it is necessary to have a projection for the potential future development of the building stock. As development of the building stock is uncertain and affected by various factors, it is important to base emission reduction strategies on transparent modelling of the building stock development. To fill this need, a transparent future projection for the quantitative development of the Finnish building stock was constructed for the study period 2020–2050. The projection of the building stock's gross floor area was calculated using the Quanti-Stock model (quantitative model for building stock development). A more detailed presentation of the model can be found in (Kurvinen, Saari, Heljo, & Nippala, 2020).

The model accounts for both regional population change and mortality of the existing building stock, both of which are discovered to be critical attributes of building stock development. Moreover, relying on the classification of buildings by Statistics Finland (2018), the model distinguishes between different types of residential and service-related buildings.

However, industrial, storage, agricultural and free-time residence buildings were excluded from the model as their heterogeneous nature makes modelling attempts inexpedient in this context. The input data relies on Official Statistics of Finland and is publicly available from the StatFin database (Statistics Finland, 2020), making it straightforward to keep the projection up to date whenever new data becomes available. By introducing a clear description of the underlying assumptions and the relatively simple modelling procedure of building stock development, this approach provides comprehensible and transparent grounds for estimating the impacts of different pathways towards the emission reduction targets. Next, the QuantiStock modelling procedure is briefly described.

2.3.1. Modelling procedure

All the components of the building stock model are presented in Fig. 4. The starting point for the QuantiStock modelling procedure was the current state of the building stock. In this study, that was the existing building stock in Finland at the beginning of 2020. Other important inputs for the QuantiStock model were the regional distribution of the population at the beginning of the modelling period and the population forecast, which in this study was available for the period 2019–2040. To cover the entire study period, the official population forecast was extrapolated to reach until the end of 2050. The raw data for the three above-mentioned input data sets were acquired from the StatFin database (Statistics Finland, 2020).

Moreover, mortality rates of the existing buildings were a central input for the QuantiStock model. First, the data to construct mortality rates of different building classes was collected from openly accessible reports from Statistics Finland. These reports account for the size of the stock for different types of buildings by the year of construction for different cross-section years. The collected data allows the formation of mortality functions for different types of buildings. Next, in a mortality sub-model, the historical mortality from mortality functions was combined with the data on existing building stock to define mortality rates for different building types. These mortality rates, which are used as an input for the QuantiStock model, were defined separately for residential buildings, public service buildings and private service buildings. The rates varied between ten-year periods.

While the data used to define mortality functions is at building stock level, the raw data from the StatFin database is reported at regional level. To keep the modelling procedure relatively simple yet accurate enough to provide relevant results, Finnish regions have been aggregated into three categories, including (1) the rapidly-growing Helsinki metropolitan area, (2) other growth regions, and (3) regions where the population has stagnated or is decreasing. The modelling of building stock development is performed separately for each of these categories and, finally, the results for different categories are aggregated to describe the development of the entire Finnish building stock. The mortality was assumed to affect the oldest part of the building stock. Some 25 % of the original building stock was modelled to have been either dismantled or altered to another purpose of use by 2050.

In the QuantiStock model, population change is used as the main predictor for the demand for residential building stock. Moreover, the *gross floor area per capita ratio* is used to assess how many square metres of each building type are needed. As attempting to guess the future demand for different types of housing units or specific types of commercial premises would only result in increased uncertainty without providing any improvement in prediction accuracy, the QuantiStock model operates with gross floor areas instead of using more detailed descriptions of building stock units. However, the distribution between

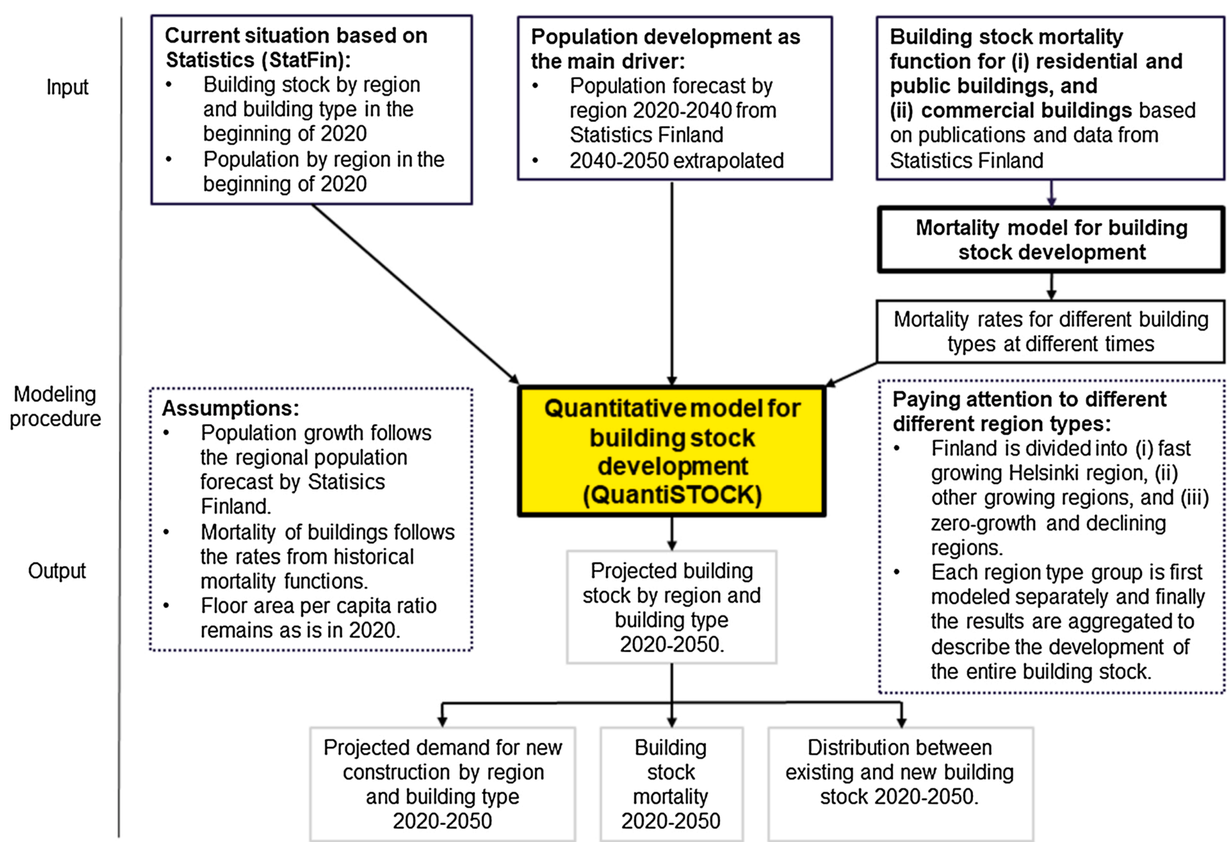

Fig. 4. The inputs and outputs of the building stock model.

(i) detached houses, (ii) semi-detached and terraced houses, and (iii) apartment buildings is specified based on official statistics, and the proportions of these different residential building types are assumed to remain at the same level throughout the study period.

As dwelling densities tend to vary due to various factors, such as residential building type and location, *gross floor area ratio per capita* was used as an input in the QuantiStock model. This allows for the inclusion of uncertainties about various factors into one predictor attribute. Those include changes in dwelling density and changes in the proportions of different residential building types. In this study, the gross floor area ratio per capita was specified based on official statistics at the beginning of the study period. For housing, the proportion of gross floor area that is reported to be 'non-permanently occupied' was excluded from the ratio. As ratios differ between different regions, a separate ratio was defined for each of the three region types. Furthermore, the ratio was assumed to remain at the same level throughout the study period.

For public service buildings and commercial buildings, the gross floor area ratio per capita is specified in the same way as for housing, with the exception that the 'not-permanently occupied' floor area of public service or commercial buildings cannot be distinguished. In the QuantiStock model, different building types are categorised based on the classification of buildings by Statistics Finland (2018). Considering the whole building stock of residential and non-residential buildings, the total built floor area was modelled to decrease by 2 % by 2050. With a new construction rate of 0.8 %/a, 23 % of the building stock in 2050 will have been constructed after 2020.

2.4. Modelling building stock power demand

To assess power demand in the entire building stock, the next phase of the analysis is to combine inputs from building-level power demand modelling and the QuantiSock model. The QuantiStock model provides the following three inputs for the building stock power demand model (PowerSock): (i) a statistical description of the Finnish building stock at the beginning of 2019, (ii) mortality rates for different types of buildings in the study period 2019–2050, and (iii) a description of the projected building stock by the end of 2050. Moreover, power demand modelling and optimisation at the building level provides hourly power demands of the selected reference buildings as input. The next step is to fit these two dimensions together by describing the entire building stock through the selected reference buildings, which are (1) multi-storey apartment buildings, (2) detached houses, (3) buildings for elderly care, (4) educational buildings, (5) office buildings and (6) retail buildings.

First, as buildings from different eras differ in terms of power demand, the gross floor area of the building stock is also divided into four age groups: (1) built in 1975 or before, (2) built 1976–2002, (3) built 2003–2009, and (4) built in 2010 or after. However, the energy performance characteristics of the different age groups were different only for the residential buildings (apartment buildings and single-family houses). For the remaining building types, the different age categories had the same characteristics. Second, buildings in different age groups are, based on official statistics, allocated to different heating systems. Third, building stock at the beginning of the study period is represented through the simulated reference buildings. Finally, the hourly power demand for the entire Finnish building stock is calculated based on the results of reference building power demand simulations. Simulations were based on test reference year weather data, which describes the current climatic conditions of Finland Kalamees et al. (2012).

The representation of the building stock through the reference buildings is not an exact match, as the power demand of every single building in the entire building stock cannot be separately modelled. However, it can be confirmed that this approach using an adequate number of reference buildings provides a close approximation to reality, as the modelled results are in line with the energy statistics at the beginning of the study period. Fig. 5 shows the comparison of energy consumption values provided by the model to those found in the Finnish statistics. For oil, wood and other fuel heating, the calculated values are based on information from the building stock registry, while the official energy statistics include some corrections made to the registry data using other sources. Non-heating electricity in the official statistics included electricity used in the vicinity of the buildings, such as street lighting and car heaters in parking spaces, which were not accounted for in the calculations of this study.

2.4.1. Retrofit scenarios towards 2050

The building stock model was used to create today's situation, which is called the Reference 2020 scenario. This was developed into the business-as-usual scenario (BAU) 2050 to show the situation in 2050 if no retrofits are done. This scenario includes building mortality and the addition of new buildings built according to the current building code Ministry of the Environment (2018). The distribution of heating systems remained the same as in the reference scenario. The other 2050 scenarios, DH Low, DH High, HP Low and HP High represent the retrofitted cases where most buildings have been retrofitted or replaced by new ones. The average combined rate of building renewal and retrofitting was 2.8 % of original building stock per year. The scenarios are summarised in Table 8. In the DH scenarios, district heating remained the dominant heating system, while in the HP scenarios heat pumps were deployed in large numbers. In the Low scenarios, buildings were retrofitted either to the lowest cost (detached houses) or cost-neutral levels (other buildings). In the High scenarios, buildings were retrofitted either in a high cost and high impact manner (detached houses and apartment

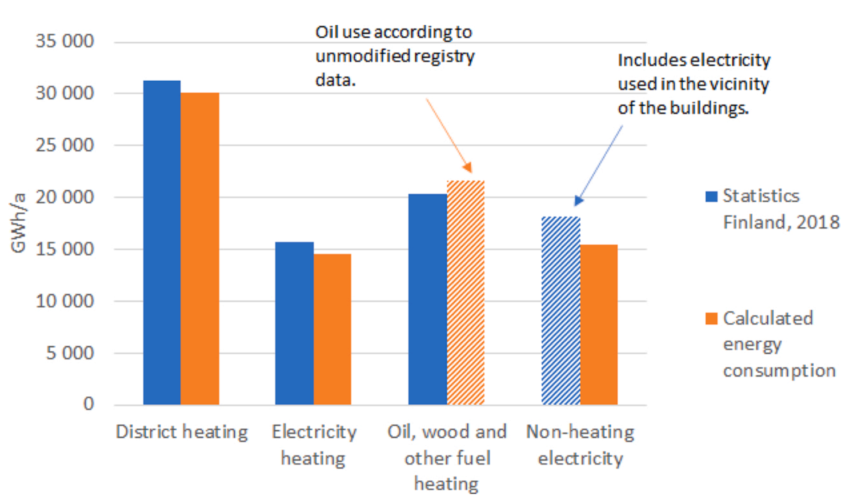

Fig. 5. Energy consumption comparison between modelled building stock and national statistics. The shaded bars signify differences in the input data.

Table 8
Scenarios for building stock development.

Scenario	Preferred heating	Climate change	Retrofit level of buildings		
			Detached	Apartment	Others
Reference	Current	No	None	None	None
BAU	Current	Yes	None	None	None
DH Low	DH	Yes	Lowest cost	Cost-neutral	Cost-neutral
DH High	DH	Yes	High cost	High cost	Cost-neutral
HP Low	HP	Yes	Lowest cost	Cost-neutral	Cost-neutral
HP High	HP	Yes	High cost	High cost	Cost-neutral

buildings) or cost-neutrally (other buildings). In the non-residential building types, only one retrofit level was used due to their smaller role in the composition of the building stock. All the 2050 scenarios also contained the effects of climate change, which reduced heating demand as estimated in (Jylhä, Jokisalo et al., 2015). In all scenarios, building mortality was assumed to occur only in the stock that was built in 1975 or before, while new construction was included in the age group of buildings built in 2010 or after.

Next, the assumptions of how heating systems are assessed to change over the study period are explained. These assumptions are based on extrapolations of historically observed behaviour and represent feasible future development scenarios.

For district heating-focused scenarios DH Low and DH High, the changes to heating systems between 2020 and 2050 are as follows:

- All buildings will keep using their existing district heating, wood heating and direct electric heating systems.
- In residential buildings with oil heating, 50 % will switch to district heating and 50 % to heat pump heating.
- In service buildings, all oil heating systems are replaced with GSHP.

For heat pump-focused scenarios HP Low and HP High, the assumptions are as follows:

- In all buildings, oil heating systems are replaced by GSHP. All buildings with wood-based or direct electric heating will keep those systems.
- In detached houses with DH, 50 % will keep using DH, while 50 % switch to GSHP. In apartment buildings with DH, 67 % will keep using DH while 33 % will switch to GSHP.
- In service buildings, 80 % of district-heated buildings will keep using DH, while 20 % will switch to GSHP.

2.5. Regional differences and climate change

The original studies for each building type utilised in the building stock calculation have been made using the test reference weather data for Helsinki, in Southern Finland Kalamees et al. (2012). This data applies for the Finnish climate zones I and II, which contain 70 % of all buildings and 75 % of the built floor area. The rest are located in the colder climate zones III (20 % of floor area) and IV (5 % of floor area). The difference in energy demand in these regions was accounted for by constant weighting factors to the demand profiles in the building stock model, such that the space and ventilation heating demand in zone III was 14 % higher than in zones I-II and demand in zone IV was 39 % higher than in zones I-II. The weighting factors were determined by simulating reference buildings using the weather data for zones III and IV and assuming the same ratio would hold for all buildings.

Since the calculation is performed for a long time period from 2020 to 2050, climate change will also start changing the energy demand in buildings (Jylhä, Jokisalo et al., 2015; Jylhä, Ruosteenoja et al., 2015). Resimulating every building using different weather files was considered too time-consuming. Instead, climate change was accounted for by constant weighting factors on all energy demand profiles, based on (Jylhä, Ruosteenoja et al., 2015). All hourly heating demand profiles were simply multiplied by constant factors so that the annual space heating demand was reduced by 16 % and ventilation heating demand by 26 %. These changes took effect on the building stock level gradually over 30 years. Climate change is also estimated to increase cooling demand, but the base cooling demand is low in Finland while cooling systems are not very common and thus cooling energy was not taken into account.

2.6. Solar electricity

At the end of 2018, the total installed grid-connected solar photovoltaic electricity generation (PV) capacity in Finland was 123 MW_p (Ahola, 2019). Between 2017 and 2018, the total installed PV capacity in Finland was increased by 53 MW. Out of the installed grid-connected PV capacity, 40 % was installed on residential buildings. A theoretical PV potential of 67 GW in Finland was suggested in (Masson & Kaizuka, 2019). However, this is very high compared to the current annual peak power demand, which is about 15 GW for the whole country.

Optimisation at the single building level produced results with high PV capacity for detached houses (Hirvonen et al., 2019b; Hirvonen et al., 2020). Assuming a single-sided pent roof sloped optimally and without shading would allow very large PV arrays to be installed. However, the most common roof type in Finland is the two-sided gabled roof, which would halve the available surface. In addition, some buildings are shaded or oriented undesirably, making solar installations unfeasible and reducing the total eligible roof area for PV installations in the building stock. It has been estimated that 25 % of roof area in detached houses could be utilised for PV on the building stock level (Niemi, 2016). Also, in retail buildings, a cost-neutral level of PV capacity would result in PV arrays double the size of the actual roof area, based on the assumption that parking spaces, etc. could be covered with PV panels. Thus, two scenarios for PV installations were considered: 1) an extreme scenario that assumes all buildings are fitted according to the individually optimised configurations, and 2) a moderate scenario where the total PV capacity in the building stock is reduced to 25 % of the extreme scenario. Climate change is expected to slightly alter atmospheric concentrations during this century. However, this is estimated to change solar radiation in Finland by only 1–5 % by 2100 (Jylhä, Ruosteenoja et al., 2015) and thus it was not taken into account.

2.7. CO_2 emissions of energy generation

The energy consumption in the building stock is made up of electricity, district heating and on-site wood or oil combustion. The emissions of electricity generation vary annually, seasonally and hourly. For this study, the average monthly emission factors of Finnish electricity generation were calculated using emission data from 2015 to 2019 (Finnish Energy, 2020a). The emission factors of electricity varied between 62 kg-CO_2/MWh during summer and 127 kg-CO_2/MWh during winter, with an average emission factor of 96 kg-CO_2/MWh (Fig. 6). For district heating, the fuel mix is much more constant and the emission factors of DH were assumed to be a constant 137 kg-CO_2/MWh (Finnish Energy, 2020b). Oil heating had emissions of 263 kg-CO_2/MWh (Statistics Finland, 2019). Within the EU Emission Trading System, biomass is assumed to have no net CO_2 emissions. The zero emission assumption was also used in this study. However, looking at the exhaust from wood combustion, the emissions of wood heating would be 403 kg-CO_2/MWh_{fuel} (Statistics Finland, 2019). This value was used during optimisation in some of the previous studies (Hirvonen et al., 2019b). It was also used for sensitivity analysis in this study.

Since the absorption of CO_2 into new biomass growth can take

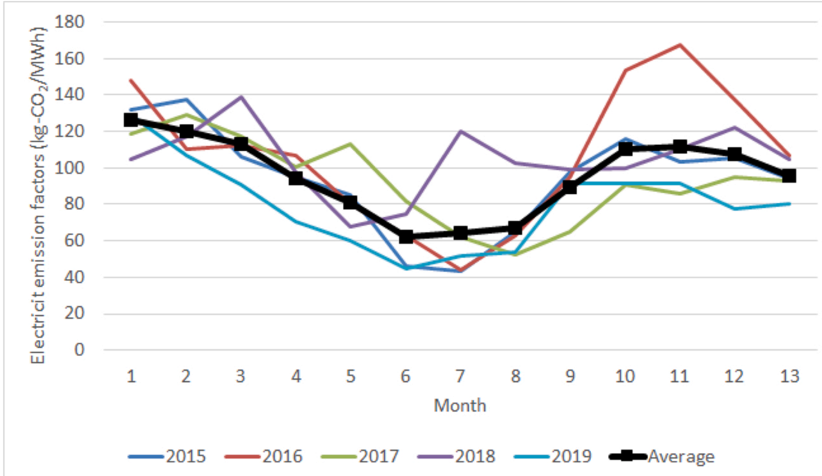

Fig. 6. Emission factors of electricity generation in Finland, not including imports or biomass emissions. The average monthly values were used in this study.

decades, it makes sense to also estimate the immediate CO_2 emissions of wood combustion, especially if the utilisation of wood fuels is expected to grow. To estimate the emissions of district heating and electricity generation using non-zero CO_2 emissions for wood, the shares of wood use in Finnish energy generation were used. According to the statistics from 2019, 39 % of district heating was generated using wood-based fuels (biomass) (Finnish Energy, 2020b). This was assumed to hold true for both Combined Heat and Power (CHP) and Heat-Only-Boilers (HOB). Some 75 % of district heating was produced by CHP and the rest by HOB. At the same time, 15 % of Finnish electricity was produced using CHP, thus the share of wood fuels in electricity generation was estimated as 5.9 %. Emissions from cogeneration were calculated using the energy method, which allocates a share of emissions equal to the share of total energy production to electricity and heat generation. According to the statistics, 69 % of CHP production was heat and 31 % was electricity (Finnish Energy, 2020b). Thus, assuming the 403 kg-CO_2/MWh_{fuel} emissions for wood combustion, the emissions for wood-based CHP electricity generation are 149 kg-CO_2/MWh. The emissions for district heating are a linear combination of 331 kg-CO_2/MWh (CHP) and 477 kg-CO_2/MWh (HOB). According to Eqs. (1) and (2), total emissions for energy generation, which includes wood-based emissions, are 280 kg-CO_2/MWh for district heating and 104 kg-CO_2/MWh for electricity. It should be noted that the distribution of CHP emissions between electricity and heat generation is somewhat arbitrary and can be done in several different ways. Here, the absolute shares of generated energy were used, which puts a larger emission burden on district heating.

The emission factor of district heating with wood-burning emissions included was calculated as

$$f_{DH\ with\ wood} = x_{wood} * (x_{DH,CHP} * f_{DH,CHP} + x_{DH,HOB} * f_{DH,HOB}) + f_{DH,cur} \tag{1}$$

where x_{wood} is the share of wood fuels in district heating, $x_{DH,CHP}$ is the share of cogeneration in district heating, $x_{DH,HOB}$ is the share of heat-only district heat generation, $f_{DH,CHP}$ is the emission factor of wood-based CHP heat generation, $f_{DH,HOB}$ is the emission factor of wood-based separate heat-only generation, and $f_{DH,cur}$ is the current district heating emission factor.

The emission factor of electricity generation with wood-burning emissions included was calculated as

$$f_{elec\ with\ wood} = x_{wood} * x_{elec,\ CHP} * f_{elec,CHP} + f_{elec,cur} \tag{2}$$

where x_{wood} is the share of wood fuels in cogeneration (assumed to be the same as in district heating in total), $x_{elec,CHP}$ is the share of cogeneration in electricity generation, $f_{elec,CHP}$ is the emission factor of wood-based electricity generation and $f_{elec,cur}$ is the current emission factor of electricity generation.

3. Results

3.1. Building stock development

The changes in the building stock from 2020 to 2050 are shown in Fig. 7. It shows that buildings removed from the building stock are all from the oldest age category, built in 1975 or before. The addition of new building is shown in the increased numbers in the 2010 age category. By 2050, most buildings have been retrofitted or replaced by new buildings. In the retrofit scenarios, the prevalence of different heating systems changed. The distribution of heating systems in the building stock in each scenario is visualised in Fig. 8.

3.2. Energy demand of the building stock

The annual energy demand of district heating and other heating, as well the electricity demand and solar electricity generation in the Finnish building stock in each scenario, are shown in Table 9. In the reference scenario, the demand for district heating, other heating and electricity are all on the same scale: close to 30 TW h each. Even in the business-as-usual scenario, they are all significantly reduced by 2050. Solar energy generation remained low.

In Table 9, 'Elec from grid' is the amount of electricity transferred from the electric grid into the buildings. This is after on-site solar electricity and transferring solar electricity between buildings has been accounted for. 'PV self' is the amount of on-site solar electricity generation used directly by the buildings, as well as transferred between the buildings. 'PV excess' is the excess on-site solar electricity production of the whole building stock that could not be utilised in the generating building nor in any other building due to lack of demand. Since energy demand is presented as positive values, the excess generation that is exported out of the building is presented with negative values. This would have to be transferred to the grid and used in some other way, such as by industries, for charging electric vehicles or by exporting to neighbouring countries. 'SF_{elec}' stands for solar fraction of electricity, which is the portion of building stock electricity demand covered by solar electricity.

The retrofit scenarios are split into two sections. The 100 % PV scenarios represent the case where solar panels were installed in all buildings according to the levels that were optimal in individual buildings. While it was the result of local optimisation, this was not considered a feasible scenario on a large scale. The 25 % PV scenarios

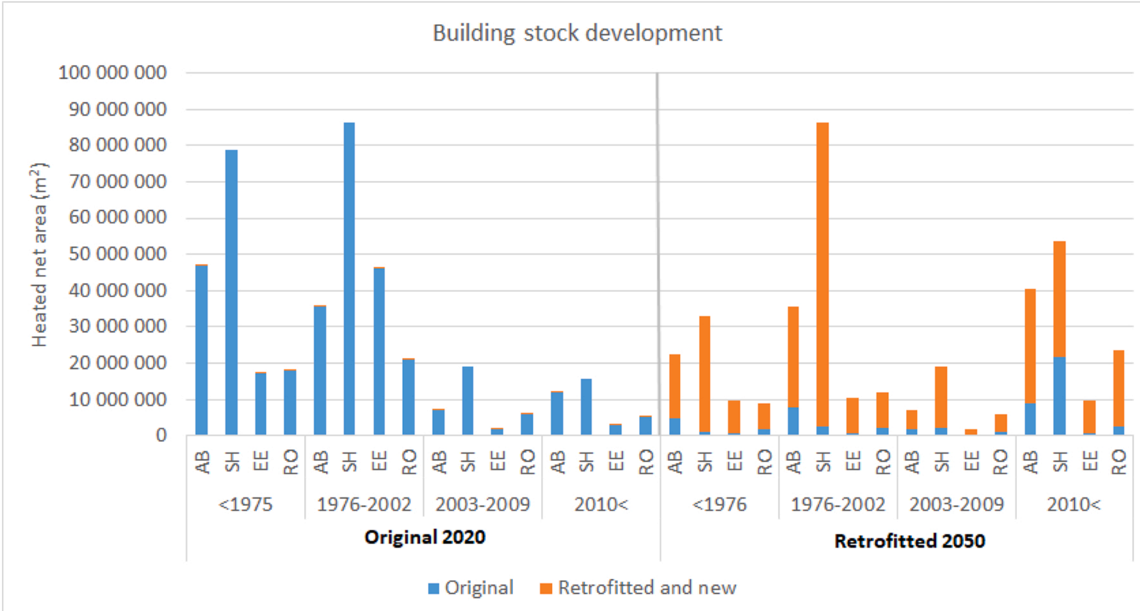

Fig. 7. Retrofitting and renewal of the Finnish building stock. The size of the building stock by building type is shown for each age class at the start and end of the retrofit scenarios. AB: apartment buildings, SH: single-family houses, EE: elderly care and educational buildings, RO: retail and office buildings.

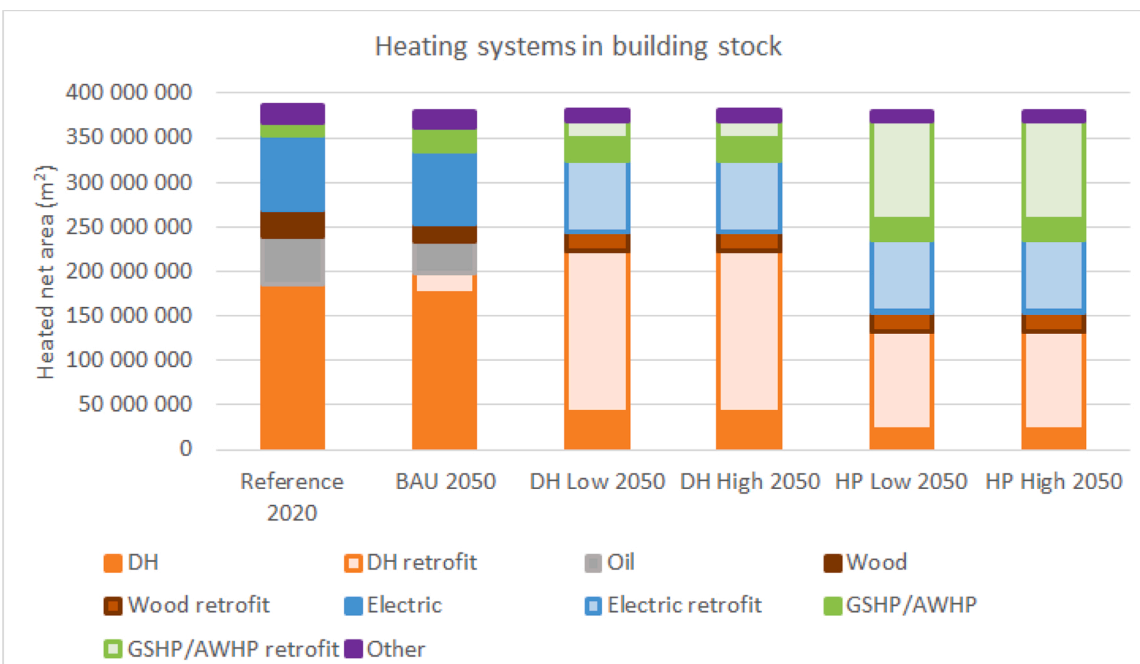

Fig. 8. Built floor areas in the building stock according to heating systems in each scenario.

represent the case where the individually optimal level of solar panels could not be installed in every building and only 25 % of the potential was realised. This was considered to be a more realistic option and was used as the basis for the rest of the scenario analysis.

In the 100 % PV cases, the total installed PV capacity was 8–13 GW_p and solar electricity generation was 9–13 TW h, of which roughly 50 % was excess power that could not be used in the building stock. In the DH High scenario, DH consumption was reduced by 43 % compared to the BAU 2050 scenario, while oil and wood heating was reduced by 80 %. Electricity consumption also dropped by 48 %. The HP High scenario focused more on heat pumps and reduced the DH consumption even more. Electricity consumption increased by 7 % compared to the district heating scenario. The difference is relatively small, because even the district heating scenario includes a large amount of air-source heat pumps, which were installed in all detached houses.

In the 25 % PV cases there was a total installed PV capacity of 2–3 GW_p and very little excess solar electricity. However, demand for grid electricity increased by 19–24% compared to the 100 % PV cases.

3.3. Power demand of the building stock

The duration curves of hourly district heating power demand for all the considered scenarios are shown in Fig. 9. The renewal of buildings through dismantling and new construction, along with climate change

Table 9
Annual energy demand of the Finnish building stock in each scenario. The cases with fully-installed PV capacity and with only 25 % installed PV capacity are shown separately.

Scenario	Non-electric heating		Electricity consumption			
	DH (GWh)	Oil and wood heat (GWh)	Elec from grid (GWh)	PV self (GWh)	PV excess (GWh)	SF_{elec} (%)
Ref 2020	30 016	27 314	29 577	264	0	0.9
BAU 2050	21 708	14 777	26 745	264	0	1.0
DH Low 2050 (100 % PV)	16 440	4 555	17 161	5 860	−3 237	25
DH High 2050 (100 % PV)	12 476	3 163	14 036	6 424	−6 135	31
HP Low 2050 (100 % PV)	9 532	4 555	18 095	6 862	−6 895	27
HP High 2050 (100 % PV)	8 074	3 163	15 067	6 576	−7 275	30
DH Low 2050 (25 % PV)	16 440	4 555	20 748	2 273	−1	10
DH High 2050 (25 % PV)	12 476	3 163	17 355	3 105	−35	15
HP Low 2050 (25 % PV)	9 532	4 555	21 579	3 378	−61	14
HP High 2050 (25 % PV)	8 074	3 163	18 262	3 382	−81	16

effects, already made a great difference, with peak heating demand falling from 15 GW to 11 GW. In the district heating scenarios, peak power fell to 8.9 and 7.5 GW for the Cost-neutral and High scenarios, respectively. For most of the year, the difference in DH power demand remained at around 0.6 GW. The scenarios with heat pump focus had an even more reduced DH demand, with peak demand at 5.7 and 5.3 GW for the Cost-neutral and High scenarios, respectively. The average difference in power demand between the HP scenarios was 0.2 GW.

Fig. 10 shows the duration curve of the hourly net electric power demand during the whole year, assuming that the individually optimal amount of solar panels (100 % PV) were installed in all retrofitted buildings. Positive values mean the demand after on-site solar power generation has been taken into account. Negative values are exports of excess on-site power from the building stock back to the national grid. Any excess power generated in one building type was first utilised in other building types before the final national excess power was calculated. The peak electric power demand was 8.2 GW in the Reference scenario and 7.3 GW in the BAU 2050 scenario. The peak power in Scenarios 2–5 were 6.7, 5.9, 8.1 and 6.6 GW. The HP Cost-neutral scenario had about equal peak power demand to the Reference case, even though the amount of heat pumps was significantly increased. While the heat pumps significantly increased the electricity consumption in many buildings, the retrofit actions in buildings with direct electric heating had the opposite effect. This is especially clear in the HP High scenario, which had the second lowest peak electricity demand of all the scenarios. High retrofits further reduced demand in both direct electric heated and heat pump heated buildings. The gap between the Reference & BAU scenarios compared to the retrofitted scenarios gets wider when approaching the right side of Fig. 10, because of solar electricity. For a total period of two months, the building stock produced more electricity than it consumed, with peak excess power reaching 10 GW in the HP High scenario. This was more than the peak demand in winter, which might cause problems for the distribution grids. Could the industry sector absorb the power or could some new uses be found, for example by charging electric cars? Such overproduction would also be problematic for the value of excess electricity and could actually prevent such a large PV penetration from happening in the first place, due to investments becoming less and less cost-effective. Because of the extreme nature of this scenario, the rest of the analysis focuses on a more moderate scenario with lower PV capacity.

Fig. 11 shows the electric power duration curves for each scenario, but with total PV capacity limited to 25 % of the configurations that were optimal on an individual building level (25 % PV). The peak power demands remained unchanged from the 100 % PV scenarios, but the average consumption levels are 200–300 MW higher. The greatest difference was in the excess power, which reached 1 GW in the heat pump scenarios, only one tenth of the excess power in the 100 % PV scenario. The number of overproduction hours remained below 200 for all except the HP High scenario.

Fig. 12 presents a closer look of the changes of each type of energy demand. It shows the hourly power demands of two-week periods in

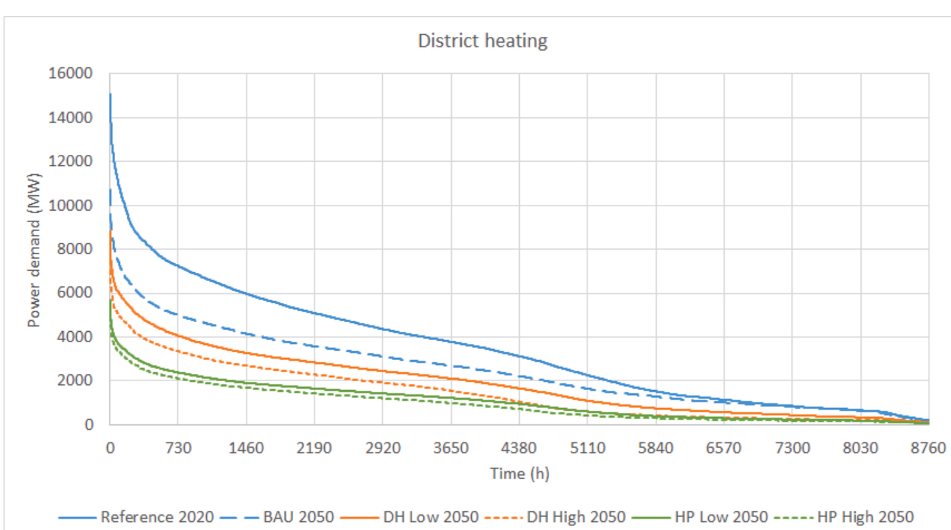

Fig. 9. Duration curve of the hourly district heating power demand in the whole building stock for each scenario.

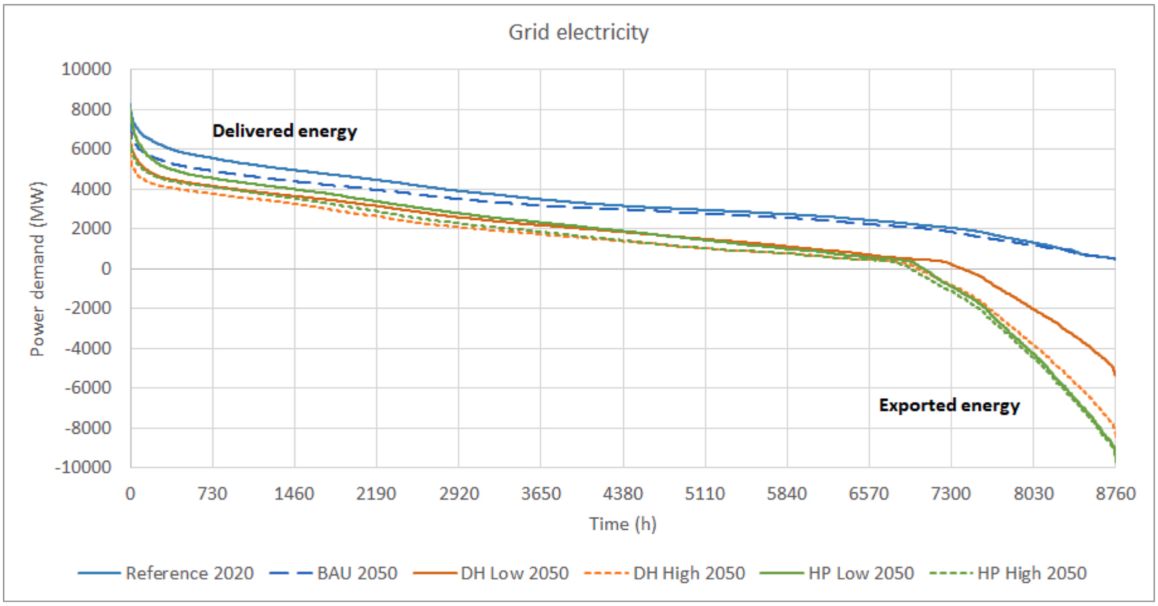

Fig. 10. Duration curve of the hourly electric power demand in the whole building stock for each scenario, if individually optimal PV capacity is installed in each building (100 % PV). Positive values are demand from the grid and negative values are excess power that is exported back to the grid.

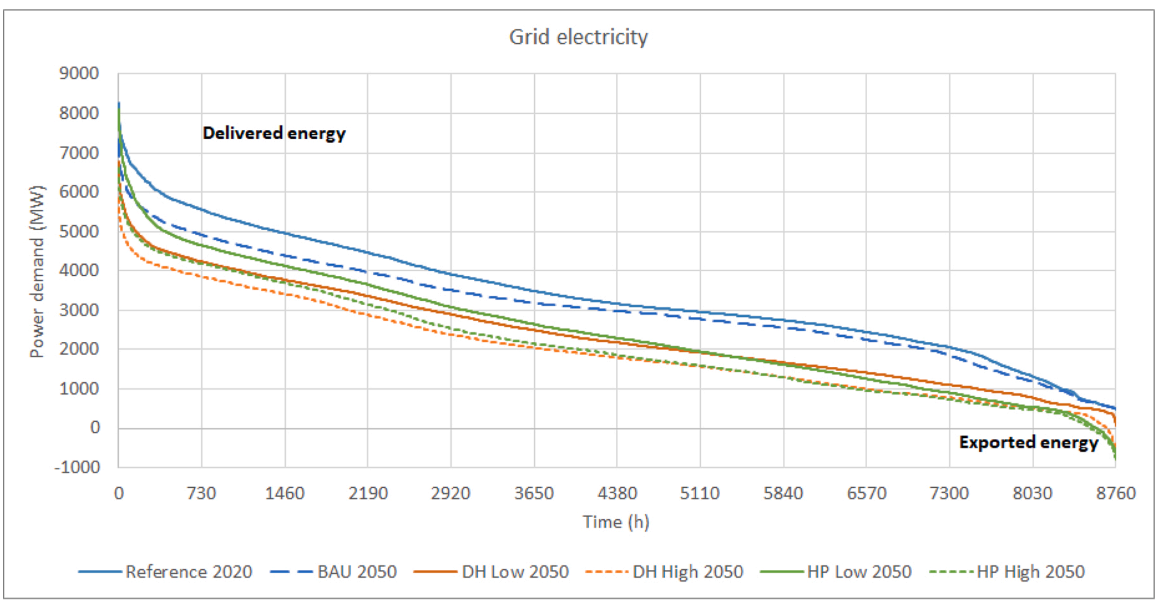

Fig. 11. Duration curve of the hourly electric power demand in the whole building stock for each scenario, if PV capacity is limited to 25 % of the individually optimal level (25 % PV).

winter, spring and summer for the Reference scenario and one retrofit scenario (HP Cost-neutral). A period of two weeks is long enough to show typical seasonal behaviour, but short enough that intraday demand changes are visible. The starting day for every plot is Monday. Here, and in all the remaining figures, the basis is the 25 % PV scenario, with only a moderate amount of solar electricity.

Fig. 13 shows the hourly district heating demand for two scenarios over three different two-week periods. The demands are separated by building type, with elderly care and educational buildings combined into the Public category and office and retail buildings combined into the Private category. Apartment buildings were the largest consumer of DH both before and after retrofits. DH demand was greatly reduced both by the building retrofits and by the changing seasons. The peak DH demand in January was over 14 GW in the Reference scenario, but only 5.3 GW HP Cost-neutral.

Fig. 14 shows the hourly electricity consumption for two-week periods in winter, spring and summer for the Reference and HP Cost-neutral scenario. The results are shown by building type and do not account for energy transfer between building types. The figure shows that detached houses dominate the electricity demand, because of electric heating and large building mass. Average power demand decreased after the retrofits, even though a lot of heat pumps were added. Air-source heat pumps in detached houses were always supporting systems only, while ground-source heat pumps were often sized to meet 100 % of demand. Sharp drops in power demand in the retrofitted January case were because of the few sunny days with very high but short-term solar power production. The gaps and drops in demand April and June were also caused by solar power. Solar power increased

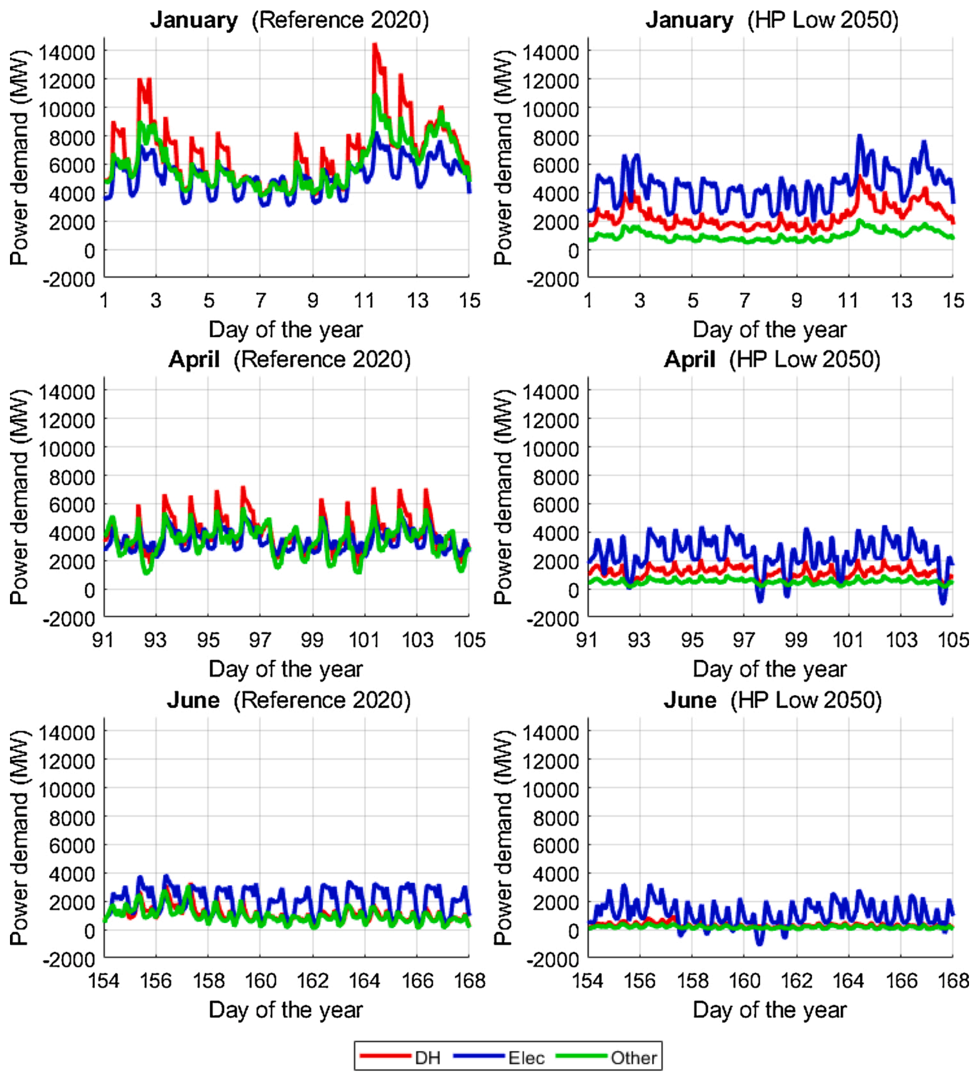

Fig. 12. Hourly power demand profiles for a two-week period in January, April and June, always starting from Monday. On the left: the reference scenario in 2020. On the right: Retrofitted scenario HP Low 2050, where the focus is on cost-neutral retrofits using heat pumps.

the fluctuation of power. Even in January, the electricity demand of apartment buildings did not rise significantly, despite the larger share of heat pumps in the retrofit scenario. However, approximately half of the oldest and least energy efficient buildings (built before 1976) were assumed to be dismantled by 2050. Thus, there were fewer buildings with the highest heating demand, limiting the rise in electricity demand.

Fig. 15 shows a monthly overview of the different demand types and the role of solar power in all scenarios. The demand for oil and wood heating in the retrofitted scenarios was greatly reduced compared to both the Reference and BAU 2050 scenarios.

3.4. CO_2 emissions of the building stock

The annual CO_2 emissions in each scenario are shown in Fig. 16. It shows how much the emissions were reduced compared to the reference case and each of the retrofit scenarios. Under EU standard practice, wood combustion is assumed to have zero emissions (a). The figure also shows how much the building sector emissions would be if emissions of wood burning were counted according to the actual CO_2 released in the process (b). Without the CO_2 from wood, the emissions in the BAU scenario were reduced to 8.1 Mt/a (−30 %), while in the best retrofit scenario (HP High) they were reduced to 2.9 Mt/a (−75 %). However, if the emissions of wood were accounted for, the same emissions were 13.6 Mt/a (−33 %) and 5.5 Mt/a (−72 %), respectively. The treatment of biomass emissions has a large effect on both the centralised power generation and the building-side boilers. The emissions in the HP High scenario increased by 85 % when biomass emissions were accounted for.

The EU target calls for carbon neutrality by 2050 (European Parliament, 2019). Total Finnish greenhouse gas emissions have gone down since 1990, from 71.5–56.5 Mt-CO_2/a in 2018, a 21 % reduction (Forsell, 2019). Thus, the remaining 79 % of 1990 emissions need to be cut in another 30 years, at quadruple the rate. After the measures done in the building stock, some additional reduction is still needed in each scenario to reach the target. Assuming that all the remaining emissions are generated in the energy sector, the target could be reached by reducing emissions from energy generation to zero.

3.4.1. Carbon budget

To remain within the Paris Agreement's 1.5 °C targets, the remaining EU carbon budget for the period 2020–2050 is about 50 Gt of CO_2 (Meyer-Ohlendorf, Voß, Velten, & Görlach, 2018). If this is distributed among member states according to population, Finland's share would be 617 Mt. Furthermore, using the proportion allocated to the building sector today (21 %), the carbon budget for the Finnish building stock would be 127 Mt. This can be compared to the cumulative emissions of the five building stock scenarios by 2050, as well the −100 % emission reduction target. The cumulative emissions in each scenario are shown in Fig. 17, assuming that constant changes in the building stock happen

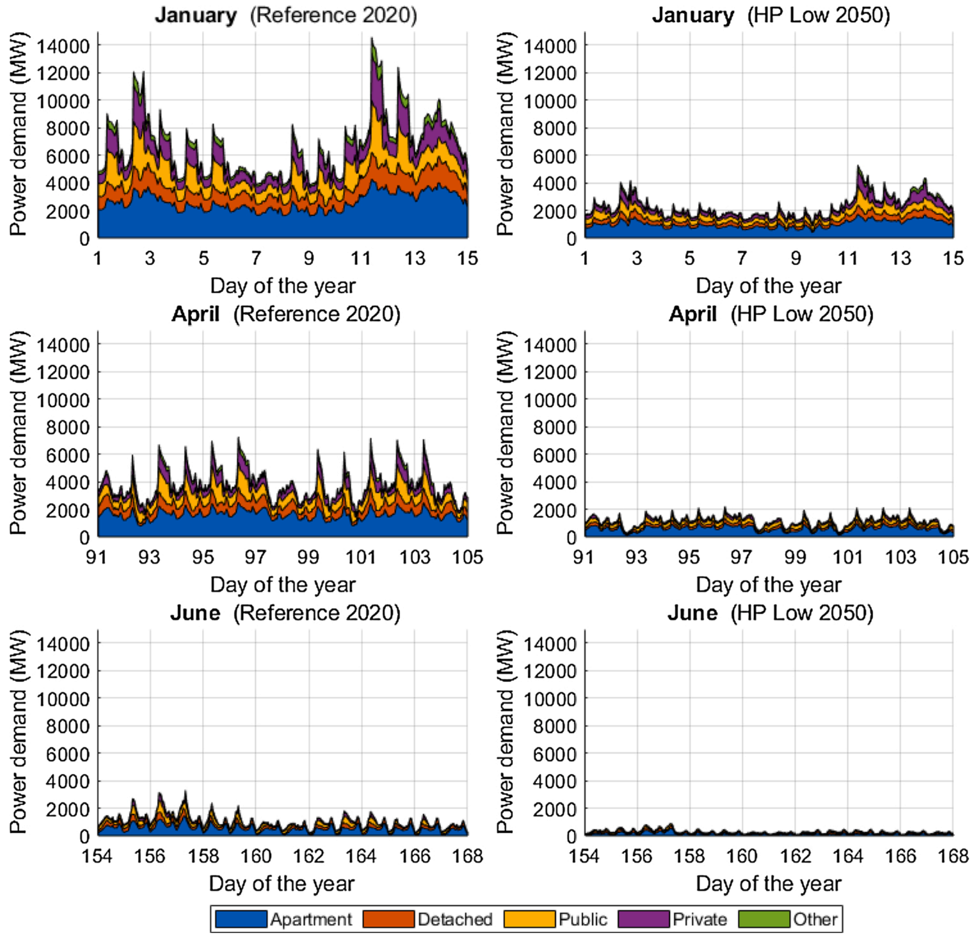

Fig. 13. District heating demand by building type during two weeks in January for scenarios Reference 2020 and HP Low 2050. The first day is Monday in each subfigure.

every year. In all 2050 scenarios, the building stock shrunk by 2 % over the whole period, as the building mortality rate exceeded the construction of new buildings. The combined rate of retrofitting and construction of new buildings was 2.8 % per year, relative to the building stock in 2020.

To remain within the carbon budget requires much higher emission reductions than just reaching the annual emission target. With fixed annual reductions, the average annual reduction rate in the BAU scenario is 1 % with respect to the starting year, while in the HP High scenario it is 2.5 %. To remain within the carbon budget requires annual reductions of 3.1 % relative to the current emissions. However, the annualised reduction does not tell the whole truth, since cumulative emissions also depend on the timing of emission reductions. Mitigation actions carried out early have a larger impact. If emissions are reduced at a constant absolute rate (Mt/a), relatively larger changes (%/a) are needed near the end of the calculation period. To remain within the budget without negative emissions, larger absolute emission reduction measures have to be implemented at the start of the calculation period. This means maintaining an annual reduction rate of 8.5 % relative to the previous year over the whole calculation period. This gives a very different impression to the annualised reductions relative to the starting year, which were 3.1 %/a. If early mitigation is not done, negative emissions are necessary to be able to remain within the carbon budget. In the Budget scenario, the annual emissions in 2035 are the same as in the best retrofit scenario (HP High) in 2050, 3.0 Mt/a. Thus, even a drastic increase in the retrofit rate would not be enough to keep the cumulative emissions below the estimated carbon budget. A decarbonised energy system is essential in reaching the goal, even in the building sector. The energy system needs to be decarbonised at a rate of 5.7 %/a, compared to the previous year, to remain within the carbon budget in the HP High scenario.

4. Discussion

When calculating the annual emissions of the building stock, the emission factors of energy generation were kept constant for the whole calculation period. However, it is expected that decarbonisation actions will be performed in the energy sector as well. Emissions from electricity generation in Finland are expected to be reduced through the expansion of nuclear and wind power capacity. Emissions from district heating will likely be reduced by the utilisation of heat pumps and the integration of waste heat recovery. Other potential measures for low-carbon district heating are seasonal thermal energy storage (Hirvonen, Rehman, & Sirén, 2018) and small modular nuclear reactors for heat production (Lindroos, Pursiheimo, Sahlberg, & Tulkki, 2019). The assumed building retrofit rates were great, but with actions in the energy generation sector, not retrofitting part of the building stock would be acceptable. This is also an expected outcome, as many buildings may be totally abandoned once the current occupants vacate them. The urbanisation trend and the reducing population of small towns increases the demand for new buildings in large cities and renders some existing buildings useless. Future trends in floor area per capita could also influence the energy consumption of the building stock. For example, a 0.5 % annual reduction or rise in floor space use could change the building stock size in Finland by a net of −8 to +10 % points (Kurvinen et al., 2020). In some buildings it might be technically infeasible to perform some of the

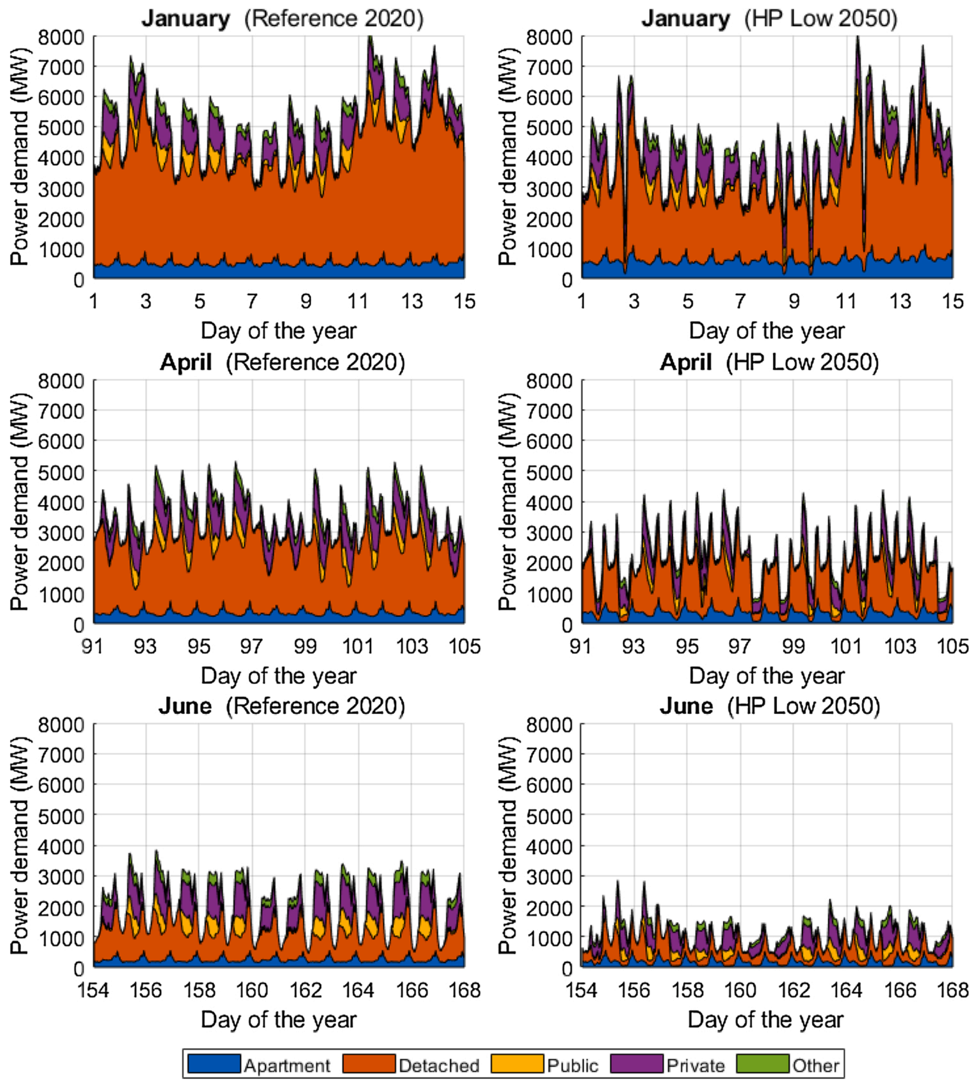

Fig. 14. Electricity demand by building type during two weeks in June for scenarios Reference 2020 and HP Low 2050. The first day is Monday in each subfigure.

proposed retrofits. In the case of solar panels, the individually optimal capacity was reduced for the building stock calculations. Since some buildings will not be retrofitted, it might be necessary to aim for a higher emission reduction goal in the buildings that will undergo retrofits, as suggested in (Rose et al., 2019).

Using the average emission factors for electricity in every case before and after retrofitting raises another issue. There is concern that increased electrification of heating would shift more demand to the margin, where it would not utilise the average generation, but the high emission marginal generation. This could cancel out the emission benefits of heat pumps. Surprisingly, this study revealed that ambitious building retrofits in electrically heated houses could actually prevent the rise of peak and average power consumption even when the number of heat pumps is drastically increased. This justifies the use of average emission factors and removes the fear of a great increase in the use of marginal electricity. Demand response is another way to mitigate the rise of peak demand. This could mean turning off some non-essential loads or lowering heating set points during peak demand. Storage of excess energy from variable renewables in batteries or hot water tanks could also help shift energy use away from peak periods.

The current EU standard is to assume the carbon emissions of wood combustion as zero, because new biomass growth will, in time, absorb the released CO_2 back into nature. However, valid reasons exist to challenge this view. Since biomass combustion is not part of the EU Emissions Trading System (ETS), its use does not require emission allowances. If a fossil-burning power plant is replaced by a biomass-burning power plant, any emission allowances previously used by the fossil plant are released to the market, allowing another fossil-burning power plant to use them instead. Because wood burning does still release CO_2, this will actually increase emissions in the short term. To best mitigate climate change and reduce the accumulation of emissions, we should focus emissions minimisation to the near future, instead of later. Even now, 36 % of the biomass used in the EU is imported from outside the EU. This can further endanger the sustainability of bio energy. There are already signs that carbon sinks in Finland are shrinking (Forsell, 2019). The total CO_2 emissions of Finland have gone down by 21 % since 1990 (Forsell, 2019). Relative to the starting level, this is 0.7 %/a. Staying within the 3.1 %/a goal determined by the carbon budget will require strong policies. At the same time, the unsustainable use of biomass needs to be avoided, so the solution has to be something other than increased wood combustion. Converting all current coal and peat power plants to use biomass would increase Finnish fuel wood consumption by 47 % (Niininen, 2021).

A source of uncertainty in the study is the use of a few building archetypes to present the whole building stock. For residential buildings, more subtypes were used, but for other building types the choices were limited. However, the objective was to see the detailed effect of implementing various technologies and generating hourly demand profiles for

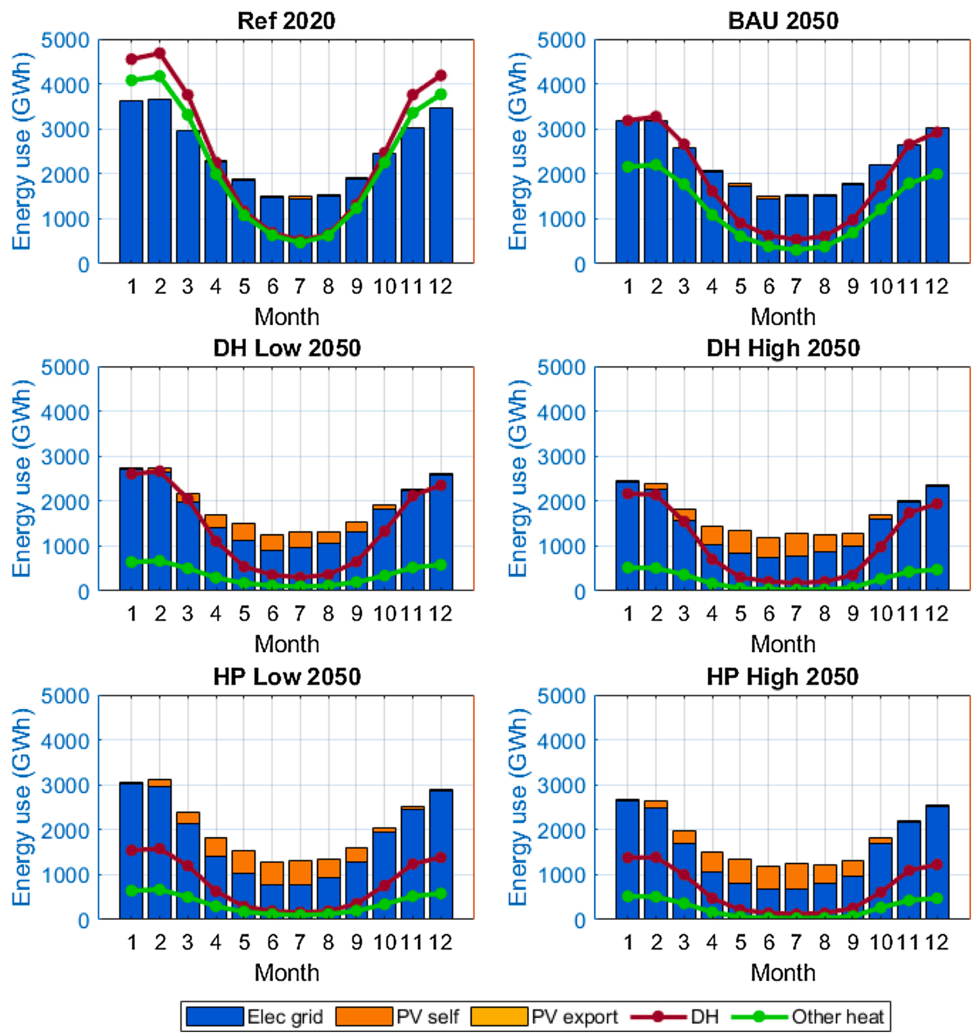

Fig. 15. Monthly energy demand of the building stock in each scenario when only 25 % of the individually optimal PV capacity is installed in the building stock level.

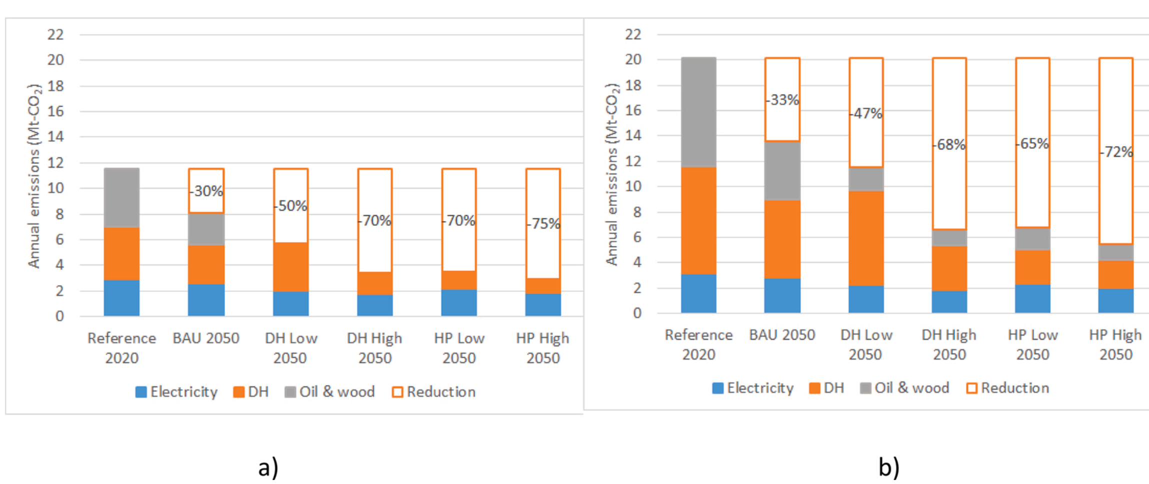

Fig. 16. CO_2 emissions of the building stock in each scenario, assuming emission factors of energy generation do not change over the 30-year period. The numbers show the emission reduction percentage with respect to current emissions. a) Wood-combustion is assumed to be carbon-neutral, b) Wood combustion is assumed to release CO_2 according to fuel statistics.

the buildings. The detailed approach limited the amount of buildings that could be used. Most Finnish buildings (75 % of floor area) reside in the most temperate climate Zones I & II (Kalamees et al., 2012). Modelling accuracy could have been increased by separate simulations for all climate zones, but due to time limitations, only constant weighting factors were used to create demand profiles for other zones.

Some equipment loads in the buildings were not included in the model. For example, lifts in apartment buildings were not included, and

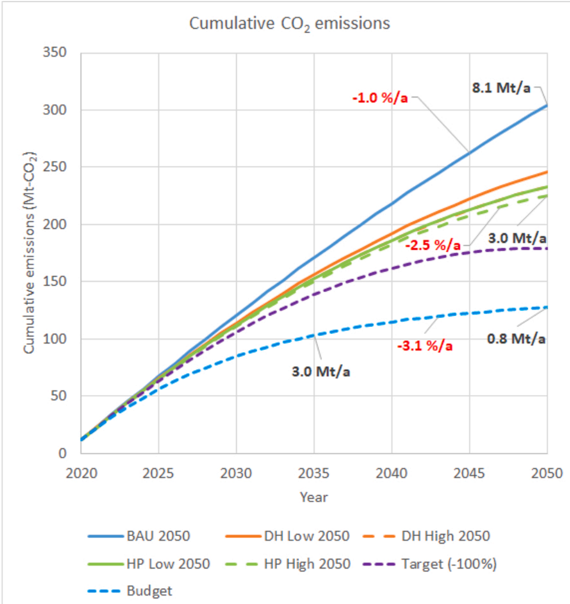

Fig. 17. Cumulative CO2 emissions over 30 years for each scenario. Emission factors for district heating and electricity are assumed to remain the same for the whole period. Also marked are the annualised emission reduction rates during 2018–2050 for some scenarios (red font) and the annual emissions during specific years in the same scenarios (black font).

nor were external loads such as outdoor lights or electric car heaters. However, as these would not be changed by the proposed retrofit measures, their influence on the end result is minimal. The change between scenarios is more important than the absolute values in each scenario. Cooling loads were also not included in the calculations. Cooling systems are not very common in Finland and the amount of cooling energy demand is only around 6 % of heating demand. Cooling demand is expected to grow by a third by 2050, even in Finland. However, as heat pumps become more common, so does the possibility for cooling. Free cooling would be enabled by GSHP systems, since the 5 ℃ ground can provide cooling without compressor use. Finnish energy utilities are also providing district cooling, which is a byproduct of district heating. Solar electricity is common in the retrofit scenarios. The highest cooling demand would coincide with peak solar energy generation in summer, which already has the lowest emission factors. For these reasons, cooling is unlikely to have a significant influence on the CO_2 emissions of the building sector in Finland.

This study focused only on the energy consumption and climate impacts, bypassing any cost analysis. The cost of large-scale energy retrofits in buildings can be examined from several points of view. From the perspective of the building owner, a short payback period is desired for an easy decision on investment. Any government grants will directly reduce costs and make the decision to retrofit easier. The building owner also benefits from the increase in real estate prices, because as much as 77 % of money invested in energy retrofits could return as increased building value (Bjørneboe, Svendsen, & Heller, 2017). However, from a societal perspective the situation changes. Government grants need to be funded from taxes and thus are not a source of direct savings. However, governments benefit from new tax income provided by jobs created by retrofitting work. It has been estimated that one million euros invested in building energy retrofits generates 17 jobs (Pikas, Kurnitski, Liias, & Thalfeldt, 2015). New employment will also reduce the cost of social assistance. Governments may directly influence retrofitting of the building stock by performing retrofits in buildings owned by the government. However, this can be challenging due to budget restrictions in different agencies as well the lack of incentives. There should be a strong mandate for performing energy retrofits in public buildings (Alam et al., 2019). This needs to be supported by procurement guidelines and facilitation teams. A dedicated financing mechanism is also required, such as a revolving loan fund, presented in (Bertone et al., 2016).

Currently, the Finnish government can get loans with negative interest rates (Bank of Finland, 2020). This enables long-term investments to be made, even in less productive projects. On the other hand, retrofits on the national scale require major investments every year for decades. An individual building owner can see the savings provided by their one big investment, but a country that invests every year will have to wait a long time until the total debt incurred will start to decrease. Analysing the cost effects of a national retrofitting programme is a good topic for additional study. In this study, only retrofit options on the building side were taken into account, while the national energy system was assumed to remain the same. These actions should be compared to changes made in the energy sector. How do emission reduction actions in buildings compare in terms of cost and impact to the construction of new low-emission power plants and other energy infrastructure? The energy demand profiles generated in this study will be used in an extension study to analyse different scenarios of power generation as well.

5. Conclusions

The Finnish building stock was modelled as a combination of six different building types. Large-scale building energy retrofits could reduce annual emissions by 50–75% if the emission factors of energy generation remain at present-day levels. If building retrofits and renewals were done at a constant rate, the cumulative emissions of the building stock by 2050 would be 225–246 Mt-CO_2. This significantly overshoots the carbon budget of 127 Mt-CO_2 that was estimated for the building sector. To remain within the carbon budget would require the energy system to reduce emissions annually by 5.7 % (compared to the previous year) for the whole 30-year calculation period. This means that emissions-reducing actions need to be frontloaded, with the most significant actions taken in the early stages of the transition to maximise the cumulative effect of the reductions. Today, 39 % of district heating is produced by wood-based fuels. If the emissions of wood-combustion were accounted for, the emissions in the best retrofit scenario were increased by 85 %.

Annual district heating energy demand was reduced by 45–58 % in the two DH-focused scenarios. With a heat pump focus, the reduction was 68–73 %. Peak electric power demand did not rise even in the heat pump scenarios, and was actually 1.6 GW lower in the HP High scenario compared to the Reference scenario and 0.6 GW lower than in the Business as usual 2050 scenario. Total electricity consumption rose in the HP Low scenario, using solutions that from the building owner's point of view paid for themselves. Electricity consumption was reduced in the HP High scenario, in which heat pump penetration was significantly increased and building energy efficiency was improved so much that the return on investment was negative. The significant increase in heat pump penetration did not increase electricity consumption, because it also replaced a lot of direct electric heating.

The building sector does not exist in a vacuum, and there are many plans to decarbonise the energy sector as well. Further studies are needed to integrate the building stock model with a model of the national energy generation system. This way, the emission factors of a changing power system will be accounted for to achieve a more reasonable estimate of emissions. In addition, the costs of large-scale building retrofitting need to be examined and compared to investments in the energy sector, in order to find a cost-effective balance between different measures. Regardless of this, fast actions are needed in the short term in both sectors, as the effects of emission reductions should be accumulated for as long as possible to minimise overshooting the carbon budget.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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